Eur J Forest Res (2012) 131:1139–1149
DOI 10.1007/s10342-011-0585-2

ORIGINAL PAPER

Greenhouse gas emissions of two mechanised wood harvesting methods in comparison with the use of draft horses for logging

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Received: 14 December 2010 / Revised: 21 October 2011 / Accepted: 22 November 2011 / Published online: 30 December 2011
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Abstract In this investigation, three different methods for the harvesting of spruce under otherwise identical conditions were analysed with respect to their greenhouse gas emissions per unit of output: a partially mechanised method using motor saws and draft horses, a more highly mechanised method using motor saws and a forestry tractor and a fully mechanised method with a harvester and forwarder. All the sub-steps from the harvesting of the fallen trees to the transportation to the road were included in the investigated greenhouse gas audit, which followed the rules of a streamlined life cycle assessment. The lowest greenhouse gas emissions were produced by the partially mechanised method (305.7 kg CO_2e ha^{-1}), followed by the more highly mechanised method (510.5 kg CO_2e ha^{-1}) and by the fully mechanised method (554.3 kg CO_2e ha^{-1}). The greatest proportion of the greenhouse gas audit within each method was taken up by the fuel, lubricant and hydraulic oil utilisation. In the horse audit, transportation to and from the site of operation caused the greatest effect (60%). With these results, it could be confirmed that horses when used for logging could be assessed as being more positive with respect to their climate friendliness than large-scale machines despite their lower harvesting capacity per hectare of spruce. However, as this study did not take all environmental impacts into consideration, this relatively better environmental audit for draft horses could be changed when other environmental impacts (e.g. land use) are also included. This possibility should be investigated in further investigations.

Keywords Greenhouse gas emissions · Life cycle assessment · Forestry technology · Timber harvesting · Draft horse

Communicated by M. Moog.

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Introduction

The use of fully mechanised forestry machines to harvest timber, especially harvesters and forwarders, has increased in importance over the past 20 years and has almost completely ousted the draft horse from the woods. This is due, on the one hand, to the large requirement for effective and rapid harvesting methods for storm-damaged wood and on the other hand, to the high demand of saw mills for short timber, which is mainly produced by harvesters. The advantages of large-scale machines in forestry work are obvious: a high power coupled with cost-effectiveness. The frequently overlooked disadvantage of these large-scale machines is, however, their high resource requirements, which are expressed as fuel use, ground pollution or as damage to the residual stand (Scharnhölz 1997).

The use of horses has been described as being uneconomic in comparison with large-scale machines (Drewes 2008). At the same time, the use of draft horses is considered as being a cultivation technique that is very gentle to the stand and they cause less logging damage due to the low pressure they exert on the ground. This in addition to their climate friendliness means that draft horses can to all intents and purposes be competitive to the use of machines (Zimmermann 1994; Wyss 1999).

Taking into consideration the United Nations' climate change agreements set-up under the Kyoto Protocol in 1997 and the reduction in emissions targets of the German government, the CO_2 audit is an important factor for the choice of wood harvesting method to be used. If wood harvesting methods were to be considered according to just this criterion, it can be assumed that the use of draft horses in forestry would be more climate friendly than the use of large-scale forestry machines. This hypothesis was investigated in this study. Many studies have already been carried out on the comparison between draft horses and forestry machines. The main focus in all these studies lies on soil compaction and damage to the residual stand caused during logging (Fleischer and Süß 2002; Scharnhölz 1997). The present-day greenhouse gas (GHG) audit represents a supplement to the aforementioned factors.

Greenhouse gas emissions stand for only a part of the whole environmental picture that is currently being intensively discussed in political circles and which is important for assessing the environmental impact of processes. The GHG audit combined with the aforementioned impacts make it possible to get a more general picture of the effects of different harvesting systems; but it is important to bear in mind that a true environmental audit is only possible when all the environmental impacts of a particular process are analysed (i.e. an entire life cycle assessment); for example, acidification potential, eutrophication, land use, energy expenditure and water consumption, all of which are strongly influenced by the harvesting system used (either draft horses or forestry machines).

The exact investigation of mechanical timber harvesting with respect to GHG emissions as well as the comparison of the results of different methods are already an important object of investigation in forestry. Important for the scheme used in this investigation is the study by Knechtle (1997), who used a method of modifying material profiles for assessing wood harvesting methods. Knechtle applied this method to two wood harvesting systems with different degrees of mechanisation and productivity and compared the systems with respect to their energy expenditure. Parts of this method and Knechtle's data are cited in the present investigation. Athanassiadis 2000, Athanassiadis et al. 2002 and Klvac et al. (2003) calculated an emission audit for different pollutant emissions in wood harvesting operations for a harvester-forwarder system under Swedish and Irish conditions. These authors took into consideration the consumption and the whole life cycle of different fuels and lubricating oils. In addition, Winkler (1997) specialised in wood harvesting methods on slopes using motor saws and other types of machinery such as helicopters. She investigated various wood harvesting systems by means of a life cycle analysis (LCA). Winkler divided the life cycle into different modules; the module 'Mechanical Production-Motor saw' is thought to be comparable with the results of the present investigation. It is important to also mention the streamlined LCA study of Sonne (2006), which examined GHG production from forestry operations. Her investigations resulted in an emission of 2.5 Mg CO_2e per 300 m^3 harvested wood if it was hand-felled and yarded using cable winches. Sonne calculated that the fuel consumption would be 15% higher if feller bunchers and skidders were used. Finally, the Timberjack Company (2002) has also undertaken an environmental audit of their own machines and found that they caused 92–95% of the environmental impact during the *Operation* phase of the life cycle, which includes the *Maintenance and repairs* as well. It is important to bear in mind that different life cycle analyses of the same product or process cannot be compared one to one easily, because researchers set different system boundaries and these have to be taken into account as they affect the results.

An audit for wood harvesting using draft horses is not known from the literature, so that the results acquired in this investigation are an addition to the mechanised investigations described above. In this investigation, the question addressed was whether draft horses are more environmentally friendly than mechanised methods with respect to GHG emissions and if yes, to what extent. For this reason, three wood harvesting methods with different degrees of mechanisation were compared with respect to their GHG emissions. The harvesting conditions were the same for all three methods.

The paper is structured as follows. The methodical framework and the sources of the used data will be explained in the second chapter. Then, the results will follow. Finally, a comparison between the three harvesting systems with respect to their greenhouse gas production is discussed in the last section.

Materials and methods

It is important for the comparison of any studies to stipulate the investigation standards that are used. The present analysis follows the guidelines ISO 14040 (2006) and ISO 14044 (2006) of a life cycle assessment (LCA) in which environmental impacts are gauged. Typical environmental impacts are greenhouse gases, ecotoxicity, eutrophication and acidification potential, land use, ozone depletion potential and abiotic resource use. Greenhouse gases represent only one impact category, so this study is a kind of streamlined LCA. The indicator GHG emissions has been chosen for this investigation due to its current topicality concerning the emissions discussion included in the Kyoto Protocol. It is important to note that GHG emissions are a good indicator for communicating the environmental effects of a process to the public at large, and the values can be used to get an impression of how a certain process can affect any future climate certificate trade. LCA studies represent a good instrument for environmental management as—by using this instrument—it is possible to examine and optimise production processes for a single product, a whole production chain or even services (Richter and Gugerli 1996; Ross 2003; Seppälä et al. 1998). Furthermore, it is possible to express the most important ecological arguments by using numerous data from the forestry sector (Zimmer and Wegener 1996).

An important example of the LCA method in forestry research is the study of Zimmer and Wegener (1996). They investigated the production of wood and wood-based products using an environmental LCA implementing the ISO 14040 and 14044 standards. For a better overview, they subdivided their life cycle in different modules; for example, 'wood production in the forest' and 'sawn timber manufacture'. A methodological comparison of the results of this study could be possible with their first module 'wood production'; however, a comparison concerning the end results is impossible because their system boundaries do not fit to the ones chosen in the present study.

As stated above, the method used in this investigation is based on the LCA procedure of the ISO 14040 and 14044 standards, where firstly, the goal and scope of the forestry investigation have to be defined. The second step is the life cycle inventory (i.e. input and output values of the processes have to be collected). The third step is the life cycle impact assessment itself, which was carried out in this study using the GHG values of the Gemis data base, Version 4.5 (2008). The last step of the LCA procedure includes the evaluation or interpretation of the results. The interpretation of the results of the present investigation is considered below in the discussion section.

The system boundaries were defined as follows: all the sub-steps within each of the three methods from the harvesting, felling, post-felling processing (e.g. delimbing, topping, measuring and sorting) to the transportation from the site of harvesting to the skid trail and from there to the road were taken into consideration and included in the calculations. The partially mechanised method utilised motor saws and draft horses. A so-called eco-forwarder was used in conjunction with the horses. This forwarder looks and works like a motor-driven forwarder with a normal crane for forwarding the logs. It has less power and weight than the other methods and is pulled by two horses. Therefore, the technical equipment of this machine is low, because the automotive part is missing. The type of forwarder considered in this study was equipped with a 14 Ps four-stroke engine for the crane, which had a maximum length of 3.5 m. In contrast to other wood harvesting methods using draft horses, this horse-drawn forwarder was used to transport the logs both to the skid trail and from there to the road. In the more highly mechanised method investigated in this study, motor saws were used for motor–manual harvesting and post-felling processing. The transportation of the logs to the road was undertaken with a forestry tractor. A harvester and a forwarder were used in the fully mechanised method.

So that the methods could be compared more easily in this investigation, it was assumed that all three methods were used in the same forestry stand—spruce with an average harvest of ca. 75 m^3 per ha—under the same harvesting conditions (skid trail interval 20 m, diameter at breast height 20 cm, soft wood; terrain flat and accessible to vehicles, able to bear a crane with a length of 6 m; mean distance for transporting the logs to the skid trail: 5 m; mean distance for transporting the logs from the skid trail to the road: 200 m). These were used as the reference values and benchmarks for each hectare. In general, in LCAs, the functional unit refers to a product or service, but in this study, one hectare is chosen as the basic unit as it refers to the area under investigation. Two additional reference values that were used were the number of cubic metres of timber harvested or the number of productive working hours (*PWH*); these will be described and discussed accordingly below.

The GHG emissions were determined using data from the literature, the machine makers and, in the case of the horse-drawn forwarders, by the questioning of practitioners. The GHG emissions factors for the calculations have been taken from the Gemis data bank, Version 4.5 (2008). The calculations of the Gemis data bank contain all the process steps from the production of the products used in the process to the fuel used for driving or transporting.

Machines for timber harvesting

To determine the GHG emissions of the machines, so-called material profiles were compiled according to Knechtle (1997). These material profiles included the four phases of the machine's life cycle: *Raw materials, Production, Operation* and *Disposal*. The raw materials were collated according to type and weight and then multiplied by their specific GHG factors. The information about the weight and type of materials was taken from Knechtle (1997), when available, or was roughly estimated. The GHG factors, as said above, were taken from the GEMIS data bank. The raw materials used in each of the machines are presented in Table 1. The data were rounded to two decimal places for the subsequent calculations.

For the GHG emissions produced during the *Production* phase, 20% of the GHG emissions for the raw materials were used according to Knechtle (1997). In the *Operation*

Table 1 Analysis of the raw materials used in the forestry machines

Material	Motor saw		Horse-drawn crane		Forestry tractor		Forestry trailer		Harvester		Forwarder		EE	GHG emissions factor
	Per cent (without blade)	Weight (kg)	Per cent	Weight (kg)	Per cent	Weight (kg)	Per cent	Weight (kg)	Per cent	Weight (kg)	Per cent	Weight (kg)	(TJ × kg^{-1})	(kg CO_2e × kg^{-1})
Steel	23.3	1.3048	90.0	1,125.0	90.7	10,702.6	90.0	4,500.0	93.0	13,671.0	91.0	10,920.0	19.742 × 10^{-6}	1.5061900
Steel (cutting blades)	–	1.1000	–	–	–	–	–	–	–	–	–	–	19.742 × 10^{-6}	1.5061900
Aluminium	30.3	1.6968	–	–	0.8	94.4	–	–	0.8	117.6	0.9	108.0	188.65 × 10^{-6}	15.2452580
Magnesium	22.1	1.2376	–	–	–	–	–	–	–	–	–	–	239.24 × 10^{-6}	16.0059730
Iron	1.8	0.1008	–	–	–	–	–	–	–	–	–	–	23.790 × 10^{-6}	1.7855270
Plastics Mean of:	22.5	1.2600	–	–	1.2	141.6	–	–	1.0	147.0	1.4	168.0	88.371 × 10^{-6}	3.1991890
PVC mix													53.818 × 10^{-6}	2.2636790
EPS													99.414 × 10^{-6}	3.63844954
Rigid PUR foam													116.08 × 10^{-6}	4.9924335
PET													98.104 × 10^{-6}	3.1637667
PP													93.809 × 10^{-6}	3.3920527
PE													69.002 × 10^{-6}	1.7447526
Rubber (incl. tyres)	–	–	10.0	125.0	6.1	719.8	10.0	500.0	4.7	690.9	6.0	720.0	94.448 × 10^{-6}	3.1757088
Glass	–	–	–	–	0.7	82.6	–	–	0.3	44.1	0.4	48.0	11.955 × 10^{-6}	1.1278529
Copper	–	–	–	–	0.5	59.0	–	–	0.2	29.4	0.3	36.0	48.982 × 10^{-6}	4.0444854
Total	100.0	6.7000	100.0	1,250.0	100.0	11,800.0	100.0	5,000.0	100.0	14,700.0	100.0	12,000.0		

GEMIS (2008); Knechtle (1997)

EE energy expenditure, *GHG* greenhouse gas

phase, the usage of fuels, hydraulic oils and lubricants was calculated, including the inputs for repairs. The data for the use of fuels and hydraulic oils were taken either from the literature or the test reports of the Committee for Forestry Work and Forestry Technology (KWF 1994, 2005, 2006a, b, 2008) and the German Association of Agriculture (DLG 2004) for the types of machines used in this investigation. These values were adapted to the spruce stand under investigation. In some cases, for example for the harvester, means have been calculated as no values were available for these particular machines. The usage of fuel, lubricants and hydraulic oils as well as their specific emissions factors and energy content (which are used to calculate the GHG emissions), and the requirement per PWH are shown in Tables 2 and 3.

The input for repairs is made up of the materials needed and the emissions that arise during the production and installation of these materials. According to Knechtle (1997) and Winkler (1997), these values are 20% of the material input required for new machines for the motor saws and 30% for the other machines. The GHG emissions for the *Disposal* phase were taken to be zero as the inputs for disposal are considered to be roughly the same as the savings involved in material recovery (Knechtle 1997; Riezinger 2008).

Table 2 Fuel, lubricant and hydraulic oil consumption in l PWH^{-1}

Forestry machine	Fuel l PWH^{-1}	Hydraulic oil l PWH^{-1}	Lubricant oil l PWH^{-1}
Motor saws	1.5[a]	0.600[b]	–
Horse-drawn crane with 14-HP motor	1.1[d]	0.005[d]	0.03[d]
Forestry tractor (Pfanzelt Pm-trac 2355)	7.0[a]	0.140[b]	0.30[c]
Forestry trailer (Pm 1590 4-WD)	–	0.140[b]	–
Harvester (1070E)	10.1[a]	0.702[b]	0.80[c]
Forwarder (810D)	7.5[a]	0.150[b]	0.30[c]

[a] KWF 1994, 2005, 2006a, b, 2008; DLG (2004)

[b] Borken et al. (1999); Schweinle and Thoroe (2001)

[c] Peters (2007)

[d] Personal communication from a German logger (horse-drawn carriage company)

[e] Own calculations with Gemis Version 4.5 (2008)

Draft horses

A complete horse lifespan was used for the draft horse audit. In agreement with Schroll (2008), the lifespan for a horse was set at 20 years. This appeared at first to be rather

Table 3 Energy content and emissions factors of the used fuels

Fuel	Energy content MJ l^{-1}	GHG emission factor kg CO_2e TJ^{-1}
Diesel (forestry)	35.87[b]	87.25×10^3[a]
Diesel (agricultural)	35.87[b]	87.30×10^3[a]
Motor saw (petrol)	32.48[b]	87.43×10^3[a]
Horse-drawn fuel-powered crane (petrol)	32.48[b]	16.03×10^3[a]
Lubricants and hydraulic oils	35.87[b]	91.33×10^3[a]

[a] Gemis Version 4.5 (2008)

[b] Arbeitsgemeinschaft Qualitätsmanagement Biodiesel e.V. (2009)

optimistic, though it can be assumed that they would be well taken care of as these animals are living capital. In addition, the investigation involved in the training of a draft horse for logging is high as it takes a long time before they can be used reliably. It can be assumed that their training will require 5 years, during which time they cannot be employed. For the residual 15 years of the horse's life, for the sake of simplicity, it was assumed that the horse had a constant work performance. The audit included the animals' feed, husbandry and transportation from the stable to the site of operation.

What was not taken into consideration was the horses' equipment (e.g. harness) as it was assumed that the required leather was produced as a by-product in beef production and has a long life, so that it could be spread out over a number of horses. Additionally, the stables were not included in the audit as it was assumed that they would be used for longer than 20 years and usually housed more than one horse. A value of zero was given for the GHG emissions for both the manure produced by the horses and their cadavers as with the disposal of the machinery, as it can be assumed that these are utilised further; for example, an energetic utilisation of the manure or a material utilisation of the cadaver, which would contribute to a positive GHG audit.

For the feed and water requirements, it was assumed that a horse requires maintenance levels during the first 5 years of life and then levels associated with heavy work for the final 15 years when it is used for logging. The requirements for an 800-kg horse, the average weight of a draft horse used in forestry, are shown in Table 4.

The GHG emissions involved in equine husbandry arise from the inputs for pasture care (haulage, fertiliser), bedding and electricity requirements. The values for these have been taken from the literature (KTBL 2005; Schroll 2008; Zeyner 2008). In addition, the distances travelled by the veterinarian and the farrier were also calculated. A veterinarian visits a horse on average twice a year; once to undertake the necessary vaccinations against rabies, tetanus, influenza and rhinopneumonitis and once for a normal visit or an emergency. It was assumed that in the optimal case, no in-depth treatment due to an accident or involving transportation to a veterinary clinic and hospitalisation was necessary. The mean route length for the veterinarian was assumed to be 25 km. The calculations used an average car as described by Gemis (2008); all the upstream chains like car production as well as fuel consumption are included in this data. It was assumed that with two horses, the veterinarian would vaccinate both animals at the same time. However, it was assumed for the visit due to unexpected reasons, the veterinarian would have to visit each horse separately once a year. As a consequence, it was calculated for the inputs that each horse would have 1.5 veterinarian visits per year, i.e., 30 veterinarian visits over 20 years. The material inputs for medication were not considered in the calculations as these would have to be apportioned between too many horses to be of any significance.

Table 4 Daily feed and water requirements of an 800-kg horse

	Maintenance requirements	Heavy work
Meadow hay (kg)	≥8	10.5
Oats (kg)	–	5
Straw (kg)	–	1.5
Concentrates (kg)	–	0.1
Drinking water (l)	32	72

Schroll (2008); Zeyner (2008)

The situation was assumed to be similar for the farrier. A farrier is called to shoe a horse every 2 months; new shoes are needed once a year. As ideally, both horses would be shoed at the same time, it was calculated that each horse would have three farrier visits per year. It should be noted that a horse is first shoed when it is in full employment, i.e., that the number of visits was only multiplied by 15 years. It was assumed that the farrier also drove an average of 25 km to shoe the horses, so that a route length of 50 km was used per visit. The means from Gemis (2008) were used for the size and fuel consumption of the farrier's transportation.

Another important factor in calculating an audit for a draft horse used for logging is the transportation of the animal to the site of operation. When machines are used for a number of days for a logging operation, they are usually driven or transported to and from the site of operation at the beginning and the end of the operation. In contrast, horses are transported back to their stable at the end of each working day. According to the information provided by a German logger, such transportation is done using a 7.5-t lorry. This is considered a standard for larger logging companies. The average distance for transportation of draft horses from the stable to the site of operation is, according to the logger, 30 km, making a daily distance of 60 km.

In the calculations, it was assumed that a draft horse fulfils an average of 1,200 PWH per year with a daily performance of 7 PWH. This means that the horses would be used for 170 days per year (Drewes 2008). Table 5 shows the requirements of the individual items necessary for the whole of a horse's life, the associated emissions factors as well as the subtotals of the GHG emissions for equine husbandry. The inputs of the two horses are included in the calculations for the horse-drawn eco-forwarders in the Results section.

Table 5 Greenhouse gas emissions in the husbandry of a horse over its whole lifespan (20 years)

	Requirements	Emission factor[c] kg CO_2e unit^{-1}	GHG emissions[d] kg CO_2e
Feed			
Meadow hay (kg)	72,087.5[a]	143.30×10^{-3}	10,330.14
Oats(kg)	27,375.0[a]	348.93×10^{-3}	9,551.96
Straw (kg)	8,212.5[a]	1.22×10^{-3}	10.02
Concentrates (kg)	547.5[a]	n.s.	n.s.
Drinking water (l)	4,52,600[a]	379.04×10^{-6}	171.55
Health care			
Farrier [distance (km)]	2,250.0[b]	168.94×10^{-3}	380.12
Veterinarian [distance (km)]	1,500.0[b]	168.94×10^{-3}	253.41
Stall			
Bedding straw (kg)	72,000.0[b]	1.22×10^{-3}	87.85
Electricity (MJ)	6,961.0[b]	259.38×10^{3}	0.00
Subtotal			20,785.05
For two horses:			41,570.10
Pasture care			
Tractor—haulage (l)	77.4[b]	87.3×10^{-3} (kg CO_2e $\times$ TJ^{-1})	242.38
Tractor—fertilisation (l)	18.6[b]	87.3×10^{-3} (kg CO_2e $\times$ TJ^{-1})	58.25
Fertiliser (kg)	1,600.0[b]	7.84	6,268.67
Means of:			
Ca Fertiliser		306.65×10^{-3}	
N Fertiliser		7.53	
Transportation			
From stable to site of operation (tkm)	153,000.0[b]	291.47×10^{-3}	44,594.91
Subtotal			51,164.21
Total			92,734.31

[a] Own calculations according to Schroll (2008) and Zeyner (2008)

[b] Own calculations according to KTBL (2005) and Schroll (2008)

[c] Gemis Version 4.5 (2008)

[d] Own calculations

n.s. not specified

Harvesting and logging performance of the different types of equipment and horses

An important influence on the energy expenditure and GHG emissions is the harvesting and logging performance. In addition, the lifespan of the individual machines has to be considered, which is orientated on the amortisation threshold. This is assumed to be 10 years for forestry machines and 3 years for motor saws. Both the performance and the lifespan of the horse-drawn forwarders were oriented on the performance of a draft horse, i.e., 15 years with 1,200 PWH year^{-1}. The lifespan (taken from the literature), the harvesting and logging performances (some estimated) and the time necessary for the harvesting or logging of a hectare for each of the individual machines are presented in Table 6. The subtotal emissions of the machines in all four phases of the life cycle are shown in Table 7. The GHG emissions are shown here both for the total lifespan of the machines and per productive working hour, which can be calculated using the information from the machine's lifespan. These data were multiplied by the harvesting or logging performance, so that the inputs per hectare could be calculated.

Using these data and Formula 1, it was possible to calculate the GHG emissions of each individual method per hectare. The summation of these values (Formula 2) then provided the total emissions per hectare.

$$E_{LP} = E * T \quad (1)$$

where E_{LP} GHG emissions [CO_2e ha^{-1}] of the life cycle phase, E GHG emissions [CO_2e PWH^{-1}] of the life cycle phase, T Time needed for the logging or harvesting of a hectare by the machine [PWH ha^{-1}].

$$E_{HM} = (E_R + E_P + E_O + E_D)_{M1} + (E_R + E_P + E_O + E_D)_{M2} \quad (2)$$

where E_{HM} total GHG emissions [CO_2e ha^{-1}] of the wood harvesting method, E_R GHG emissions [CO_2e ha^{-1}] for the raw materials, E_P GHG emissions [CO_2e ha^{-1}] for production, E_O GHG emissions [CO_2e ha^{-1}] for operation (including the use of horses), E_D GHG emissions [CO_2e ha^{-1}] for disposal, M_1/M_2 timber harvesting or logging machines 1 and 2.

In this investigation, no more than two machines were used in any of the three wood harvesting methods.

Table 6 Lifespan and harvesting and logging performance of the machines and horses

Machine	Lifespan			Average performance for harvesting or transportation of logs in m^3 PWH^{-1}	Time requirements for a hectare spruce with 74.75 m^3 PWH ha^{-1}
	PWH $year^{-1}$	Years	PWH (total)		
Motor saws	450[a]	3	1,350[a]	2.50[d]	29.90[h]
Eco-forwarder	1,200[b]	15	18,000[b]	3.82[b]	19.57[h]
Forestry tractor	1,500[h]	10	15,000[c]	6.00 [g]	12.46[h]
Harvester	1,865[c]	10	18,650[c]	8.75[e]	8.54[h]
Forwarder	1,720[c]	10	17,200[c]	8.90[f]	8.40[h]

[a] Klugmann (2006)

[b] IGZ (2000c); Schroll (2008)

[c] Nick and Forbrig (2002)

[d] EST (1977)

[e] Schweinle and Thoroe (2001); Nick and Forbrig (2002); FPP (1998); Pröll (2004)

[f] Nick and Forbrig (2002); Bacher-Winterhalter (2003); Schweinle and Thoroe (2001)

[g] Graupner and Hauck (1999)

[h] Own assumptions and calculations

Results

With 305.7 kg CO_2e ha^{-1}, the partially mechanised method (using horses) had the lowest GHG emissions followed by the more highly mechanised method (510.5 kg CO_2e ha^{-1}) and the fully mechanised method (554.3 kg CO_2e ha^{-1}). The absolute and proportionate (as a percentage) GHG emissions in kg CO_2e ha^{-1} of the whole method, each of the individual machines and the different phases of the life cycle are shown in Table 8.

In the partially mechanised method, the proportion of the total emissions caused by the draft horses is 33%, whereby 60% of this is caused by the transportation of the horses to the site of operation. Two other large proportions of these emissions are due to the feeding of roughage (12%) and concentrates (15%). In comparison, the inputs for water (1%), farrier and veterinarian (together 2%), pasture care (5%) and the stables (5%) tended to be rather insignificant.

Despite its high harvesting capacity, the fully mechanised method produced the highest amount of GHG emissions per hectare. This, therefore, confirms the thesis that the use of draft horses for forestry work is more climate friendly with respect to GHG emissions than the use of machinery. A comparison of the results per hectare, productive working hour and cubic metre is shown in Table 9. The tendencies of the results of the three harvesting methods are the same for all three reference values. The partially mechanised method always has the best results with respect to GHG emissions. However, the higher GHG emissions with the more highly mechanised method with respect to working hour can be brought more into perspective if its higher harvesting and logging performance are taken into consideration.

In the calculation of the GHG emissions for each method with respect to the productive working hours, it should be taken into consideration that not only the subtotals should be summated but that the performance of the less efficient machine determines the overall performance of the method. For example, if the motor saw in the more highly mechanised method has a total performance of 2.5 m^3 PWH^{-1}, then this will be the performance of the forestry tractor (i.e. the tractor will only run for ca. 40% of its working hours and so will produce less GHG emissions and use less energy than if it was being used at full capacity). As the majority of the inputs are involved in the operation of the machines, then this was the approach used for the more highly mechanised and the fully mechanised methods. This was not done with the partially mechanised method because the upkeep of a horse continues even when it is not working; so in this case, the complete value per working hour was chosen.

Discussion

Although both the more highly mechanised and fully mechanised methods are indeed standard forestry methods, this is not the case with the partially mechanised method. The latter is one that can only be found in niches (for example, water protection areas) where the use of heavy machinery is not possible or not allowed. The implementation of horses for logging is often combined with a forwarder or forestry tractor, which transports the logs from

Table 7 Greenhouse gas emissions in each of the four phases of the machines' life cycles

Phase of life cycle	Motor saw		Horse-drawn crane		Forestry tractor + trailer		Harvester		Forwarder	
	kg CO_2e PWH^{-1}	kg CO_2e (total)	kg CO_2e PWH^{-1}	kg CO_2e (total)	kg CO_2e PWH^{-1}	kg CO_2e (total)	kg CO_2e PWH^{-1}	kg CO_2e (total)	kg CO_2e PWH^{-1}	kg CO_2e (total)
Greenhouse gas emissions										
Raw materials	0.04[e]	53.51[a]	0.12[e]	2,091.44[a]	1.38[e]	28,995.83[a]	1.35[e]	25,217.13[a]	1.23[e]	21,117.91[a]
Production	0.01[e]	10.70[b]	0.02[e]	418.29[b]	0.28[e]	5,779.17[b]	0.27[e]	5,043.43[b]	0.25[e]	4,223.58[b]
Operation										
Fuel	4.26[d]	5,751.00[e]	0.57[d]	10,260.00[e]	21.91[d]	328,650.00[e]	31.61[d]	589,526.50[e]	23.47[d]	403,684.00[e]
Lubricant	1.97[d]	2,659.50[e]	0.02[d]	360.00[e]	0.92[d]	13,800.00[e]	2.30[d]	42,895.00[e]	0.49[d]	8,428.00[e]
Hydraulic oil	–	–	0.10[d]	1,800.00[e]	0.98[d]	14,700.00[e]	2.62[d]	48,863.00[e]	0.98[d]	16,856.00[e]
Repairs	0.01[e]	10.70[c]	0.03[e]	627.43[c]	0.41[e]	8,698.75[c]	0.41[e]	7,565.14[c]	0.37[e]	6,335.37[c]
Disposal	0.00[b]	0.00[b]	0.00[b]	0.00[b]	0.00[b]	0.00[b]	0.00[b]	0.00[b]	0.00[b]	0.00[b]

[a] Gemis Version 4.5 (2008); Knechtle (1997); IGZ (2000c)

[b] Gemis Version 4.5 (2008); Knechtle (1997); Riezinger (2008)

[c] Gemis Version 4.5 (2008); Knechtle (1997); Winkler (1997)

[d] Gemis Version 4.5 (2008); Arbeitsgemeinschaft Qualitätsmanagement Biodiesel e.V. (2009)

[e] Own calculations

the slipway to the road. The horses are only used for work within the stand (i.e. the transportation of the logs from the site of harvesting to the slipway). The harvesting of the trees with this method is also motor manual.

With the same harvesting conditions for all three methods, the GHG emissions with the partially mechanised method (draft horses combined with forwarder or forestry tractor) would be about 430 kg CO_2e ha^{-1}, which is obviously lower than for both the more highly mechanised method and the fully mechanised method. Due to the lower GHG emissions, it should be considered whether it would not be a positive development to use more horses in forestry work in combination with forwarders, especially as this method also has a better performance with respect to soil compaction and conservation of the stand (Fleischer and Süß 2002; Scharnhölz 1997). However, it should also be taken into consideration that other environmental impacts may have a determining effect on the environmental audit of processes like harvesting systems; for example, it is possible that draft horses could have a greater impact on land use or acidification than forestry machines.

This study considers only some environmental impacts, not all of them. Certainly, it can be dangerous to make conclusions about a process when only a selected few of the environmental impacts are considered. A recently published case that shows how dangerous partial environmental audits can be is that of the packaging used for the *Danone activia* yoghurt pot (Kauertz et al. 2011). In this study, packaging made from fossil fuel-based polystyrene and organic polylactide (based on polylactide acid produced from corn) was compared. Certain environmental impacts like the low consumption of fossil resources and GHG emissions were found to have a positive environmental assessment for the organic polylactide packaging, while agricultural land use and the effects on water and soil (e.g. pollution) were found to be negative with respect to the fossil fuel-based plastic. The authors, themselves, came to the conclusion that the organic packaging had the same environmental impact as the fossil fuel-based packaging as although the latter utilises more fossil fuel resources it needs less land for its production. This in itself shows how the inclusion of all environmental factors is necessary before a decision is made about whether a process is more environmentally friendly or not. However, the Danone case also shows another danger: the facts that were communicated to the public at large were only those of the positive side of the audit for the organic packaging, leading to a misinformed assumption that the organic packaging was better for the environment than the fossil fuel-based one.

The results shown in Table 9 with respect to the hectare, productive working hours and to amount of wood produced emphasise the effects of using a different reference value on the outcome of the calculations. One could debate about which of these three reference values is the best one to use. In previous publications, as a rule, the results were based on the working hours when a complete method chain was presented. The reference value 'cubic metres of timber harvested' was chosen when only machines (i.e. individual sections of a method) were compared to each other. In contrast, in this investigation, a hectare with potentially the same yield was chosen as the reference value, so that the same harvesting conditions could be used for all three methods. It is, however, generally difficult to compare the use of horses with the use of heavy machinery in forestry because the former method is usually used on sites that are often less

Table 8 Greenhouse gas emissions of the individual machines and methods in kg CO2e and percentage per hectare spruce stand

Partially mechanised method	Motor saw		Eco-forwarder	
Phase of life cycle	kg CO_2e	%	kg CO_2e	%
Raw materials	1.20	0.39	2.35	0.77
Production	0.30	0.10	0.39	0.13
Operation	186.58	61.03	114.88	37.58
Fuel	186.28	60.94	13.50	4.42
Horses	–	–	100.79	32.97
Repairs	0.30	0.10	0.59	0.19
Disposal	0	–	0	–
Total	188.08	61.52	117.62	38.48
More highly mechanised method	Motor saw		Forestry tractor	
Phase of life cycle	kg CO_2e	%	kg CO_2e	%
Raw materials	1.20	0.2	17.19	3.3
Production	0.30	0.1	3.49	0.7
Operation	186.58	36.6	301.78	59.1
Fuel	186.28	36.5	296.67	58.1
Repairs	0.30	0.1	5.11	1.0
Disposal	0	–	0	–
Total	188.08	36.9	322.46	63.1
Fully mechanised method	Harvester		Forwarder	
Phase of life cycle	kg CO_2e	%	kg CO_2e	%
Raw materials	11.53	2.1	10.33	1.9
Production	2.31	0.4	2.10	0.3
Operation	315.47	56.9	212.61	38.4
Fuel	311.97	56.3	209.50	37.8
Repairs	3.50	0.6	3.11	0.6
Disposal	0	–	0	–
Total	329.31	59.4	225.04	40.6

Table 9 Energy expenditure and greenhouse gas emissions of the machines and methods according to different reference values

	Greenhouse gas emissions		
	kg $CO_2e \times ha^{-1}$	kg CO_2e m^{3-1}	Kg CO_2e PWH^{-1}
Method			
Partially mechanised	305.70	4.10	12.30
More highly mechanised	510.54	6.83	17.08
Fully mechanised	554.34	7.41	64.90
Machine			
Motor saw	188.08	2.51	6.29
Horse-drawn forwarder	117.62	1.59	6.01
Forestry tractor with trailer	322.46	4.32	25.88
Harvester	329.31	4.40	38.56
Forwarder	225.04	3.01	26.79

lucrative than those where machinery is used. Indeed, large-scale machines would also have a below-average harvesting or logging capacity on such problem or marginal sites due to their problematical topography and difficult driving and harvesting conditions.

As the results show, transporting the horses to the site of operation involved ca. 60% of the total emission production. This is a clear disadvantage in comparison with the forestry machines because while these remain overnight in the woods, the horses have to be transported back and forth to their stables each day. To reduce this factor, the draft horses could be left at the site of operation as many modern transporters are capable of providing stabling for horses for a number of days. In addition, the cart horses used for such work are robust and not very demanding with respect to their stabling requirements.

In the partially and more highly mechanised methods, the motor saw produced a large part of the emissions. This is a consequence of the saw having a two-stroke engine that produces a large amount of emissions. In the future, it would be better to use a motor saw with a four-stroke engine to improve the environmental audit. The usage of alkylate petrol and catalytic converters can also greatly reduce emissions. Stadler et al. (1999) calculated in their investigation on a small four-stroke engine a reduction in emissions of ca. 90% when alkylate petrol and a three-way catalytic converter was used.

Although the results are different, the tendencies of the individual machines are comparable to the tendencies found in other investigations analysing the use of harvesters and forwarders in forestry work (Klvac et al. 2003; Athanassiadis 2000; Athanassiadis et al. 2002). These differences are due to the different classes of machine being used and the different assumptions about fuel use. In addition, many of the values used in the present study are averages, so that differences will arise in comparison with other studies. The results of Sonne (2006) show that she found 15% more GHG emissions in the fully mechanised system than in the partially mechanised system; in the present study, the difference between the two degrees of mechanisation is much higher (over 80%). The reason for this is that different machines were assessed in the study done by Sonne (2006). As stated before, LCA studies on the use of draft horses are not known in the literature as such, but other LCA studies in the forestry sector that concentrate on GHG audits have comparable methodologies and result tendencies. The results of this investigation are an important contribution as they show the advantages of using draft horses in forestry work in general and not just on problem or marginal sites.

Another interesting point of investigation would be a comparison of machines fuelled by 2nd-generation biofuels made from hay in comparison with horses fed on hay. Assuming the use of 2nd-generation biofuels, the more highly mechanised and the fully mechanised harvesting systems could have much better GHG audits than they have in the present study. For a detailed comparison with the partially mechanised system, the fodder conversation efficiency of the draft horses would have to be taken into consideration. This would make interesting research for further studies.

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