Carbon Footprint of Forest Operations under Different Management Regimes

Giulio Cosola, Stefano Grigolato, Pierre Ackerman, Sergio Monterotti, Raffaele Cavalli

Abstract

Different forest management regimes have different carbon footprints due to alternative operational strategies and options. Data concerning CO_2 *emissions (kg* m^{-3}*) in felling, extraction, comminution and transport operations, performed under two different forest management regime (close-to-nature and plantation), were collected through a systematic literature review involving 162 scientific papers and compiled into a database. Results show that, within limits, forest operations in plantations produce lower emissions due to easier operational conditions, while transportation in both close-to-nature and plantation based forest operations reported the highest levels of emissions. Literature came from a variety of sources and often differed in context due to factors such as technology, work technique, operator skill and environmental conditions. These factors have been shown to highly affect the results obtained from the studies. Nevertheless, it has been possible to summarize most of the information gathered and to highlight the most representative driving factors in* CO_2 *emissions throughout different forest management regimes.*

Keywords: CO_2 *emissions, forest management regimes, forest operation, carbon footprint, wood harvesting, wood extraction, wood transport*

1. Introduction

Forest ecosystems store more than 80% of all terrestrial aboveground C and more than 70% of all soil organic C (Jandl et al. 2007). As a consequence, the ever increasing concentrations of carbon dioxide (CO_2) in the atmosphere have highlighted the importance of forests as a mitigation agent (IPCC 1993, Routa et al. 2012).

Globally, forest vegetation and soils contain about $1146x10^{12}$ kg of C, 37% of which is found in low-latitude forests, 14% in mid-latitude forests and 49% at high-latitude forest (Dixon et al. 1994). The annual CO_2 exchange between forests and the atmosphere via photosynthesis and respiration accounts for about 50×10^{12} kg of C per year, approximately 7 times that caused by anthropogenic sources (Jandl et al. 2007). Accordingly, forests are considered important in limiting the increase in atmospheric carbon dioxide since trees sequestrate substantial amounts of carbon from the atmosphere to be stored in both above and below ground biomass through the process of photosynthesis.

However, during forest harvesting operations, carbon is released to varying degrees depending on the product being harvested and on emissions from the machines used in the process (Liski et al. 2001). Principal sources of CO_2 in forest operations result from direct core emissions related to fuel used by machines (Knechtle 1997, Schwaiger and Zimmer 2001, Klvač et al. 2003, Gonzalez-Garcia et al. 2009a, Gonzalez-Garcia et al. 2009b, Valente et al. 2011, González-García et al. 2012, Klvač et al. 2012, Picchio et al. 2012, Vusić et al. 2013). However, these emissions are rather low when considered in a global context (Berg and Lindholm 2005). For example, in countries with high forest coverage, such as Sweden, these specific emissions amount to about 1% of total national emissions (Athanassiadis 2000).

CO_2 emissions in forest harvesting operations are also influenced by stand and terrain conditions, wood species, management methods, operator performance and machinery limitation or design (Van Belle 2006, González-García et al. 2009a, Gonzalez-Garcia et al. 2009b, Kärhä 2011, Vusić et al. 2013, Alam et al. 2014).

Therefore, with increasing mechanization of forest operations, it can be expected that emissions could increase (Berg 1997, Athanassiadis 2000) even though forestry activities do not tend to emit vast amounts of greenhouse gases (*GHG*).

The necessity for a low carbon emission system still exists, bearing in mind that *GHG* emissions in the European Union must be reduced by 40% by 2030 (with 1990 as base-line). This proposed reduction must, however, be cost effective and sustainable in the long run (EU 2014).

The aim of the present work is to investigate, by using the data retrieved by a systematic review on the scientific literature published over a period of 20 years, the different carbon footprints due to various operational strategies and options occurring under specific forest management regimes and highlight the general principles that can be recognized in order to enforce more environmentally friendly harvesting practices.

2. Materials and Methods

2.1 Systematic review

To synthesize and discuss issues and findings of CO_2 emission from forest operations, a systematic review was conducted to retrieve relevant scientific publications over the last 20 years (1994–2014).

A systematic review consists in a process of identifying and evaluating multiple studies on a topic using a clearly defined methodology (Wolf et al. 2015).

In our case, literature search was located by Scopus and Google Scholarsearch engine using English search terms and their various combinations applying Boolean operators (*AND OR*), wild-cards (for any group of characters (*) or for a single character (?)) (the search strings were combined as follow: 1. *AND* 2. *AND* 3.).

1. Search string for forest and forest products:	»forest*« *OR* »stand« *OR* »*wood*« *OR* »*timber« *OR* »spruce« *OR* »beech« *OR* »pine« *OR* »poplar« *OR* »eucalyptus« *OR* »plantation« *OR* »close-to-nature«
2. Search string for forest operations:	»operation« *OR* »logging« *OR* »harvest*« *OR* »forward*« *OR* »extraction« *OR* »skid*« *OR* »*haulage« *OR* »transport*« *OR* »machin*« *OR* »*mechaniz*«
3. Search string for emissions:	»emission?« *OR* »CO_2« *OR* »*GHG*« *OR* »greenhouse*« *OR* »fuel consumption« *OR* »productivity« *OR* »rate« *OR* »time« *OR* »*LCA*« *OR* »life cycle«

The search was carried out in the context of »Forestry, Agriculture and Environmental Science« or »Engineering« and only articles reporting results about CO_2 emissions in forest operations were analyzed.

In addition, information not specific to CO_2, but that could be worked back through to calculated emissions, was used.

To assist the search, an »Evidence-Based Approach to Scoping Reviews« was followed based on the following methodology (Landa et al. 2011):

1) Define and refine research search terms,
2) Identify databases and search engines and query using the search terms,
3) Create and apply the inclusion and exclusion criteria filters,
4) Verify that the sub-selections are representative.

2.2 Database

All the identified literature was re-organized into a database built in Microsoft Access®. The framework of the database (Fig. 1) is taken up in the following tables:

⇒ Literature,
⇒ Emissions,
⇒ Survey,
⇒ Machine technical data.

In the Literature table, all the principal features of analyzed the papers were reported, such as the Title, Year, Author/s and Country. A link to the relative Portable Document Format (PDF) file was also provided. The Emissions table, in which all the most relevant data and values were collected, was connected with the Literature table through a »one-to-many« relation between the *ID* field, where a unique *ID* identified each paper. Another »one-to-many« relation connected the Survey table to the Emission table through the field »*ID_S*« (survey). In the former, specific data of the field survey areas were reported when available. The database also included specific tables containing technical data on the relative categories of machines (e.g., harvester, forwarder, slash bundler, skidder, tractor, cable yarder, excavator, chipper and truck) according to the way in which information was provided by each study. They were then simply connected to the Emission table through the field »*ID_M*« (machine).

2.3 Boundaries and Functional Unit

The boundary of the study was fixed to activities performed under two different forest management approaches [close-to-nature silviculture (*CTN*) and plantation (*P*)] and related to the harvesting site and the transport of forest products. Harvesting operations were considered as carried out under semi-mecha-

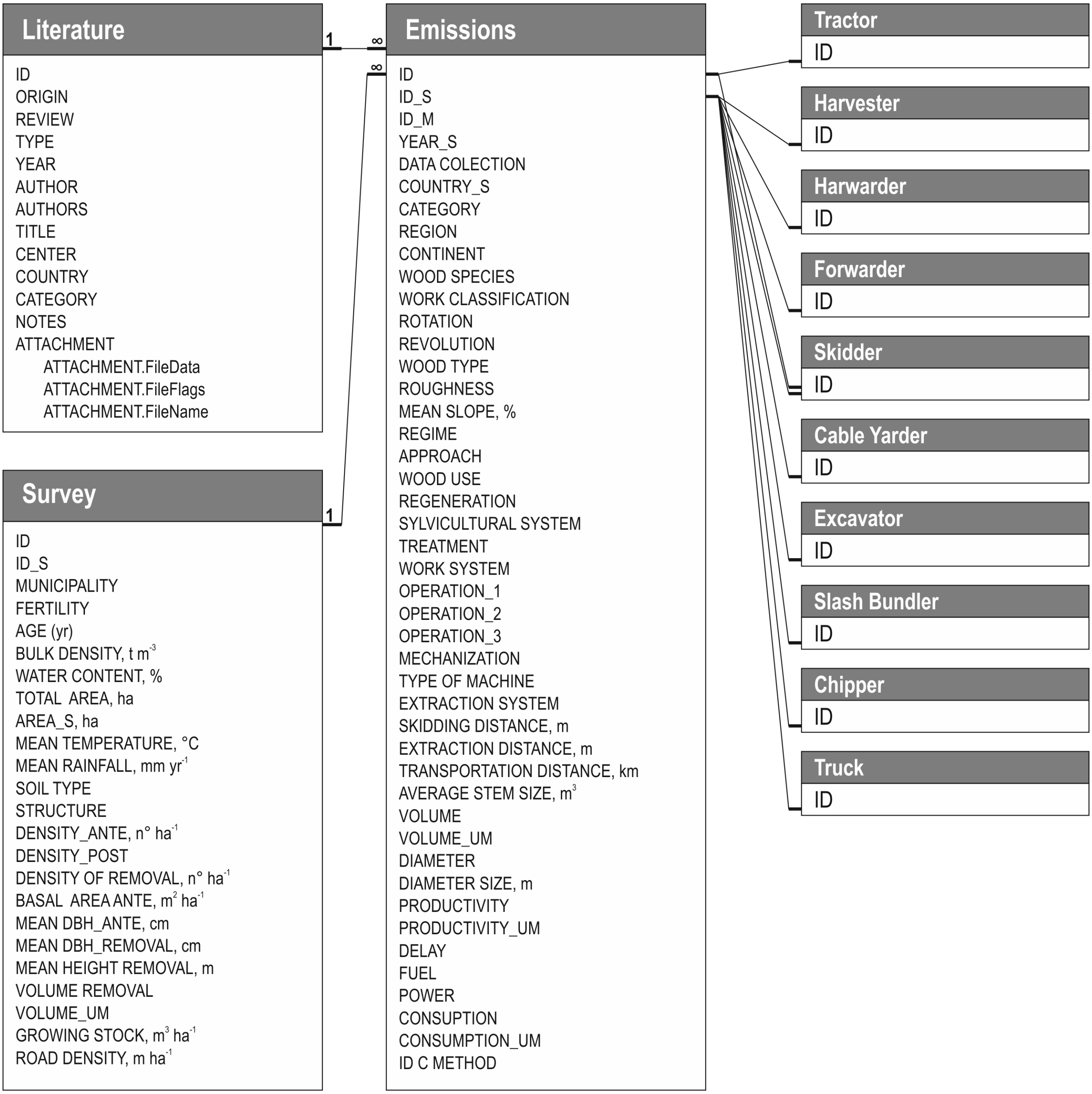

Fig. 1 Framework of the CO_2 Database showing the relationships between different tables

nized (*SM*) and fully mechanized (*FM*) levels. Hence, only data on emissions from the functional phases of felling, extraction (primary transport) and transportation (secondary transport) were collected. Other work stages typical of forestry operations in plantation, such as site preparation and tending, were not considered.

The functional unit (*FU*) was expressed as kilograms of CO_2 directly emitted for every cubic meter of fresh (moisture content of 50%) wood processed and then expressed in kg CO_2 m^{-3}. Even if, at times, it was possible to distinguish between over bark (o.b.) and under bark (u.b.) diameter, this distinction was eventually not used. »Directly emitted« means that only core direct emitted CO_2 (EPA 2008) was considered. The choice of considering only CO_2 gas lies in the fact that it represents the main air pollutant factor in terms of Global Warming Potential (*GWP*) (González-García et al. 2009a, Gonzalez-Garcia et al. 2009b), whereas all other gases represent only a minimal percentage, with a total amount less than 1% (Gillenwater 2005).

Table 1 Simple emission factors reported in some studies

Fuel	CO_2	Emission unit	References	Used for
Diesel	2.65	kg l^{-1}	(Holzleitner et al. 2011)	Trucks
Diesel	2.672	kg l^{-1}	(Devlin et al. 2013)	Trucks
Diesel	2.6569	kg l^{-1}	(Zorić et al. 2014)	Trucks
Diesel	2.6	kg l^{-1}	(Korpilahti 1998)	Forwarders, chippers and trucks (Diesel density of 840 g/l is assumed)
Diesel	3	kg l^{-1}	(Van Belle 2006)	Chippers [Coefficient derived from (CWAPE 2002)]
Diesel	3.188	kg kg^{-1}	(Karjalainen and Asikainen 1996)	Heavy-duty diesel vehicles and farm equipment [Coefficient derived from (IPCC 1993)]
Diesel	73.3	g MJ^{-1}	(Karjalainen and Asikainen 1996)	Heavy duty diesel vehicles and farm equipment [Coefficient derived from (IPCC 1993)]
Diesel	982	g km^{-1}	(Karjalainen and Asikainen 1996)	Heavy duty diesel vehicles and farm equipment [Coefficient derived from (IPCC 1993) and assuming moderate control and fuel economy of 2.8 km l^{-1}]
Diesel	74.06	g MJ^{-1}	(Dias et al. 2007)	Different machine and equipment [Coefficient derived from (Perry and Green 1997, Normand and Treil 1985)]
Diesel	74.10	g MJ^{-1}	(Valente et al. 2011)	Different machine and equipment [Coefficient derived from (IPCC 2006)]
Diesel	78.15	g MJ^{-1}	(Engel et al. 2012)	Different machine and equipment [Coefficient derived from (Öko-Institut 2008)]
Diesel	78.20	g MJ^{-1}	(Engel et al. 2012)	Different machine and equipment [Coefficient derived from (Öko-Institut 2008)]
Diesel*	260	g MJ^{-1}	(Athanassiadis 2000)	Different machine and equipment [Coefficient derived from engine test and must be assuming a 40% thermal efficiency of the engines]
Gasoline	78.31	g MJ^{-1}	(Engel et al. 2012)	Chainsaw [Coefficient derived from (Öko-Institut 2008)]
Gasoline	14.36	g MJ^{-1}	(Engel et al. 2012)	Horse-drawn trailer equipped with an engine powered crane [Coefficient derived from (Öko-Institut 2008)]
Gasoline	69.30	g MJ^{-1}	(Dias et al. 2007)	Different machine and equipment [Coefficient derived from (Öko-Institut 2008)]

* Environmental class 3; Environmental class 1; Rapeseed Methyl Ester

In fact, CO_2 equivalent (CO_{2eq}) considers the sum of the three principal gases such as CO_2, N_2O and CH_4 weighted for their *GPW* for a time horizon of 100 years with reference to CO_2 *GWP* (IPCC 2006). Methane and N_2O emissions depend not only upon fuel characteristics, but also on the engine combustion technology type, conditions within the engine combustion chamber, usage of pollution control equipment, and local environmental conditions (Lloyd and Cackette 2011). When weighted by their Global Warming Potentials (*GWPs*), CO_2 typically represents over 99% of the *GHG* emissions from the stationary combustion of fossil fuels (Gillenwater 2005). So, in those cases conversion to normal values of CO_2 was achieved using a conversion factor of 0.99 (Gillenwater 2005).

All retrieved papers were divided in three groups according to the origin of the emission values:

⇒ Emission: papers in which CO_2 emission values are stated;

⇒ Fuel consumption: papers in which CO_2 emission values are not stated, but they can be extracted through direct or indirect measurement of fuel consumption;

Life Cycle Assessment (*LCA*): papers in which emission CO_2 and *GHG* emissions are provided in the measuring and assessing procedures of environmental performance of forest operations by isolating, when possible, base values of CO_2 from the rest of the information provided.

2.4 Emissions

Emissions analyses are mostly done in an indirect manner. Only one study reports the amount of exhaust emissions calculated by a portable emission measurement system (Lijewski et al. 2013).

In all the other studies, more attention was paid to variables and coefficients used according to machine and physical fuel characteristics. Different analysis

Table 2 Calorific value of fuels

Fuel type	MJ l^{-1}	References	Used by
Diesel	36.14	(Alt1n et al. 2001)	Self-determined
Diesel	36.55	(McDonnell et al. 1999)	(Klvač and Skoupý 2009)
Diesel	37.00	(Bailey et al. 2003)	(Spinelli and Magagnotti 2013)
Diesel	38.60	Supposed	(Routa et al. 2011)
Diesel	35.87	(AGQM 2009)	(Engel et al. 2012)
Diesel	36.29	(IPCC 2006)	(Valente et al. 2011)
Diesel	38.65	(EPA 2008)	Self-determined
Diesel	36.83	(Normand and Treil 1985) and (IPCC 2007)	(Dias et al. 2007)
Diesel	35.30	(SEA 2008)	(Lindholm et al. 2010)
Swedish environmental class 3	36.00	(Furuholt 1995; Grägg 1999)	(Athanassiadis 2000)
Swedish environmental class 1	35.30	(Grägg 1999)	(Athanassiadis 2000)
Rapeseed methyl ester	33.10	(Grägg 1999)	(Athanassiadis 2000)
Blend of semi-refined rapeseed oil (25%) and Diesel fuel (75%)	35.67	(McDonnell et al. 1999)	Self-determined
Gasoline	34.48	(Perry and Green 1997) and (IPCC 2007)	(Dias et al. 2007)
Gasoline	34.63	(EPA 2008)	Self-determined
Gasoline	32.48	(AGQM 2009)	(Engel et al. 2012)

methods have been developed during the past decades by both researchers and national agency teams to address this problem. Important values have been collected, analyzed and, if necessary, used in this study in order to process other similar available data. The studies, whose results have been computed through the use of coefficients or equations from other studies, were marked in the database with the *ID* code of the respective study. In the simplest cases, a coefficient for liter or MJ of fuel consumed (Table 1) was applied to obtain a value for CO_2 emitted.

Energy content or calorific value (*CV*) of fuels also varied between studies. Data concerning the leading references of the values, the references and in which paper they were used are reported in Table 2.

Some studies offered more complex equations, which were used if they could be fitted to the specific case (Table 3).

2.5 Fuel consumption

Fuel consumption (*FC*) is defined as the amount of fuel in liters (l) consumed by a machine during one working hour (h), and its measurement unit is expressed as $l\,h^{-1}$. In emission analysis, fuel consumption is indeed an important value when CO_2 emissions are computed indirectly.

From 1994 to 2014, a total of 118 studies including direct or indirect fuel consumption values were identified.

During the considered time period (1994–2004), some equations were proposed and used to compute fuel consumption indirectly for different forest harvesting systems (Table 4). In order to measure indirectly the fuel consumption, it is also significant to mention the generic formula proposed in the FAO Forestry Paper 99 (FAO 1992).

2.6 *LCA*

LCA studies in forestry have a wider context than the ones dealing with machine emission and fuel consumption and report values of CO_2 and other *GHG* emissions relative to energy consumed. From 1994 to 2014, a total of 27 studies were identified.

In most cases, *LCA* calculations relate to machine construction, repairs and other materials involved. The more complex part is the interpretation of the results to isolate base values of CO_2 from the rest of the information provided. Moreover, and despite efforts by ISO 14400, the major drawback of *LCA* studies is the lack of uniformity in variables and scope (Berg 1995, Schwaiger and Zimmer 2001, Heinimann 2012).

Table 3 Paper whose CO_2 emission equations have been used in the database calculations

Equations and References	
Dias et al. (2007) $SE_{ij} = EWT_i \cdot C_{ij} \cdot VW_j \cdot CEF_j \cdot NCV_j \cdot FCO_j \cdot \frac{44}{12} \cdot 10^{-3}$ Where: SE_{ij} is CO_2 specific emissions associated with operation i due to the consumption of fuel *j*, g CO_2 ha^{-1} or g CO_2 $m^{-3}{}_{ub}$ EWT_i is effective work time of operation *i*, h ha^{-1} or h $m^{-3}{}_{ub}$ C_{ij} is consumption of fuel *j* in operation *i*, l h^{-1} VW_j is volumetric weight of fuel *j*, kg m^{-3} CEF_j is carbon emission factor of fuel *j*, kg C GJ^{-1} NCV_j is net calorific value of fuel *j*, MJ kg^{-1} FCO_j is fraction of carbon oxidized of fuel *j*	
Density and carbon content approach (EPA 2008) $E_{ec} = \sum_{i=1}^{n} F_i \cdot FD_i \cdot C_i \cdot FO_i \cdot \frac{CO_{2(m.w.)}}{C_{(m.w.)}}$ Where: E_{ec} is Emission from Energy (fuel) Consumption, g FU^{-1} F_i is volume of Fuel Type *i* combusted FD_i is density of Fuel Type *i*, mass / volume C_i is Carbon Content Fraction of Fuel Type *i*, mass C / mass fuel FO_i is Fraction Oxidized or Fuel Type *i*	Klvač and Skoupý (2009) $E_{ec} = FC \cdot EF \cdot CV \cdot TE$ Where: E_{ec} is Emission from Energy (fuel) Consumption, g FU^{-1} FC is Fuel Consumption, l FU^{-1} EF is Emission Factor, g MJ^{-1} CV is Calorific Value, MJ l^{-1} TE is Thermal Efficiency, %

Table 4 Fuel consumption equations specifically developed for different forest harvesting systems

Equations and References	
(Nordfjell et al. 2003) $y = -0.110 + 0.00047 \cdot x$ Note: Specific for forwarder VALMET 890 (130 kW), in Pine stand for loads of saw-logs already stacked $y = -0.026 + 0.001 \cdot x$ Note: Specific for forwarder VALMET 890 (130 kW), in Pine stand for loads of saw-logs already stacked Where: y is fuel consumption, l $m^{-3}{}_{ub}$ x is average extraction distance, m	(Nordfjell et al. 2003) $y = 0.288 + \left(\frac{0.00638}{L}\right) \cdot d$ Where: y is fuel consumption, l $m^{-3}{}_{ub}$ L is load size, $m^3{}_{ub}$ d is average extraction distance, m Note: Generic for forwarder in a Pine stand with easy condition terrain for final felling, with loads of both sawlog and pulpwood already stacked
Freitas (2004) $y = 0.134 \cdot x$ Where: y is Fuel Consumption, l PMH_0^{-1} x is Power of machine, kW Note: Generic, in clear-cutting system stand conditions (coppice stem selection and pre-commercial thinning are excluded)	Klvač and Skoupý (2009) $y = 8.203 \cdot e^{3.655 \cdot x \cdot 10^{-3}}$ Where: y is Fuel Consumption, l PMH_0^{-1} x is Power of machine, kW Note: Generic, for harvesters and forwarders in clear felling

However, *LCA* provides a systematic way to measure and assess the environmental properties of products and processes (Athanassiadis et al. 2002) along with the methodology on how to conduct these studies. Unfortunately, the technical parameters required for analysis, such as fuel consumption or CO_2 emissions, are not usually measured. These parameters are rather collected from interviews, technical specifications, agency reports or scientific articles. Hence, in many cases their results are meaning less from an operative point of view, as they do not represent anything outside of pure coefficients used for estimations (even if they are properly chosen by Authors). Beyond these aspects, in many cases, parameters used in *LCA* studies came from findings already analyzed and recorded in the database, so their retrieval has been avoided to minimize redundancy in the results.

3. Results

3.1 Forest operation CO_2 emissions

Values of CO_2 emissions related to 523 different forestry operating conditions were thus recorded in the database and were analyzed at various levels of detail. A general analysis follows in the subsequent three sections referred to as the three phases of »harvesting« (felling and extraction), »chipping« and »transport«.

3.1.1 Felling and primary transport

In the *CTN* management system, values of 6.69 kg CO_2 m^{-3} and 3.94 kg CO_2 m^{-3} are, respectively, found for *FM* and *SM* harvesting systems. In *P* management system, values of 5.80 kg CO_2 m^{-3} and 3.52 kg CO_2 m^{-3} were recorded for the same harvesting systems.

FM harvesting system seems to show a higher impact (Table 5) than *SM* system in terms of CO_2 emissions, both in *P* and *CTN* management approaches. This is mainly due to the use of chainsaws instead of self-propelling machines (Berg 1997), which can also be seen in Table 6. Lower average emissions in the *P* approach are likely due to easier and more productive working contexts.

Table 5 Comparison of CO_2 emissions in harvesting operations (felling and extraction), according to different management approaches (*P* – Plantation or *CTN* – Close-to-nature) and mechanization levels (*FM* – Fully mechanized or *SM* – Semi-mechanized)

	Observations	Average	Max.	Min.
	N	kg CO_2 m^{-3}		
SM (CTN)	9	0.62	2.48	0.10
FM (CTN)	16	6.64	41.83	1.17
SM (P)	3	0.85	1.01	0.69
FM (P)	8	4.23	10.02	1.75

Table 6 Comparison of CO_2 emissions in felling operations, according to different management approaches (*P* – Plantation or *CTN* – Close-to-nature) and mechanization levels (*FM* – Fully mechanized or *SM* – Semi-mechanized)

	Observations	Average	Max.	Min.
	N	kg CO_2 m^{-3}		
SM (CTN)	23	0.63	2.48	0.10
FM (CTN)	158	3.66	70.17	0.87
SM (P)	4	0.60	1.01	0.02
FM (P)	39	3.94	16.35	0.55

When splitting harvesting into its two components, felling (Table 6) and extraction (Table 7), the latter presents higher average values of emissions at the semi-mechanized level. This is in accordance with its generally less productive context (selective cutting, steep terrain, vulnerable sites). Reasons behind CO_2 emissions patterns can be found among fuel consumption and productivity factors, such as machine type, logistic organization, stand characteristics, type of treatment, site conditions and of course, operator skill and attitude (Nordfjell et al. 2003, Kärhä et al. 2004, González-García et al. 2009a, Gonzalez-Garcia et al. 2009b, Alam et al. 2014).

Table 7 Comparison of CO_2 emissions in extraction operations, according to different management approaches (*P* – Plantation or *CTN* – Close-to-nature) and mechanization levels (*FM* – Fully mechanized or *SM* – Semi-mechanized)

	Observations	Average	Max.	Min.
	N	kg CO_2 m^{-3}		
SM (CTN)	36	4.26	11.06	0.24
FM (CTN)	67	3.04	6.77	0.97
SM (P)	6	2.92	5.9	1.14
FM (P)	11	2.25	5.18	0.42

Focusing on *SM* extraction, differences in emissions do not seem to depend on the type of extraction system used, i.e. Ground Based System (*GBS*) or Cable Based System (*CBS*). Table 8 reports that there are minimal differences between these systems (4.01 kg CO_2 m^{-3} for *GBS* and 4.42 kg CO_2 m^{-3} for *CBS*).

Table 8 Comparison of CO_2 emissions in extraction operations, according to different extraction systems (*GBS* – Ground based system and *CBS* – Cable based system) in *CTN* (Close-to-nature) management approach

	Observations	Average	Max.	Min.
	N	kg CO_2 m^{-3}		
GBS (CTN)	14	4.01	9.33	0.24
CBS (CTN)	22	4.42	11.06	1.15

Table 9 Comparison of CO_2 emissions in extraction operations with *GBS* (Ground based system), according to different management approaches (*P* – Plantation or *CTN* – Close-to-nature) and mechanization levels (*FM* – Fully mechanized or *SM* – Semi-mechanized)

	Observations	Average	Max.	Min.
	N	kg CO_2 m^{-3}		
SM (CTN)	14	4.01	9.33	0.24
FM (CTN)	66	3.04	6.77	0.97
SM (P)	6	2.92	5.90	1.14
FM (P)	11	2.25	5.18	0.42

Greater differences can be found within the *GBS* itself than between the various levels of mechanization or management approaches (Table 9).

The organization at landings depends on machines available and site conditions. Table 10 presents emissions for harvesting according to three main silvicultural treatments of *CC* (clear cutting), *SHW* (Shelter-Wood Cutting) and *SC* (selective cutting).

SHW and *SC* treatments show higher values of emissions in the *FM* context. This is in accordance with the higher percentage of wood harvested by thinning operations (where productivity of mechanized felling can be severely affected due to tree size and working conditions) when compared to *CC* treatment.

SHW treatment implies a natural regeneration, which is why no data were available for the *P* management approach (Table 10).

In the case of *CC* in *P*, preparatory thinning practices such as early thinning (*ETH*) or thinning (*TH*) made before a final cutting (*FC*) were also considered. Data about thinning considerably affected the results, as shown in Table 11.

In both *P* and *CTN* management approaches, fully mechanized thinning operations (*ETH* and *TH*) emit more CO_2 per cubic meter than final cutting (Berg 1997). The same pattern occurs for semi-mechanized operations in *P* management approaches, whereas an opposite effect is seen in *CTN*. In this case, the results are mostly influenced by the emissions during extraction operations that, as mentioned above, are associated with a more difficult working environment.

Table 10 Comparison of CO_2 emissions in harvesting operations (felling and extraction), according to different management approaches (*P* – Plantation or *CTN* – Close-to-nature), mechanization levels (*FM* – Fully mechanized or *SM* – Semi-mechanized) and silvicultural treatments, such as *CC* (Clear cutting), *SHW* (Shelterwood cutting) and *SC* (Selective cutting). *SC* and *SHW* cuttings belong only to the *CTN* management approach, because no data considering the *P* management approach were available

		Observations	Average	Max.	Min.
		N	kg CO_2 m^{-3}		
CC	*SM (CTN)*	18	4.72	11.83	2.32
CC	*FM (CTN)*	138	4.68	11.76	1.94
CC	*SM (P)*	10	3.53	6.92	1.14
CC	*FM (P)*	49	5.73	21.53	0.97
SHW	*SM (CTN)*	40	3.67	11.81	1.25
SHW	*FM (CTN)*	94	9.44	75.28	2.82
SHW	*SM (P)*	N/A	N/A	N/A	N/A
SHW	*FM (P)*	N/A	N/A	N/A	N/A
SC	*SM (CTN)*	9	2.27	6.72	0.10
SC	*FM (CTN)*	6	7.45	9.20	5.86
SC	*SM (P)*	N/A	N/A	N/A	N/A
SC	*FM (P)*	N/A	N/A	N/A	N/A

3.1.2 Chipping

In many circumstances, timber harvesting includes the chipping of the residues or of the whole trees. Chipping can be done directly in the stand using small machines. With easy terrain accessibility, it can be done at the roadside using more powerful machinery or at a terminal with either mobile and/or stationary machinery (Liška et al. 2010). Average values found for *CTN* and *P* approach are reported in Table 12.

Even in chipping, it appears that the *P* context has less of an impact with 5.36 kg CO_2 m^{-3} emissions compared to 9.70 kg CO_2 m^{-3} in the *CTN* management approach.

Table 11 Comparison of CO_2 emissions in harvesting operations (felling and extraction), according to different management approaches (*P* – Plantation or *CTN* – Close-to-nature), mechanization levels (*FM* – Fully mechanized or *SM* – Semi-mechanized) and silvicultural treatments such as *ETH* (Early thinning), *TH* (Thinning) and *FC* (Final cutting)

		Observations	Average	Max.	Min.
		N	kg CO_2 m^{-3}		
ETH	*SM (CTN)*	2	2.69	2.84	2.55
ETH	*FM (CTN)*	14	6.95	9.10	5.20
ETH	*SM (P)*	1	5.90	–	–
ETH	*FM (P)*	13	9.15	19.88	6.12
TH	*SM (CTN)*	2	2.69	2.84	2.55
TH	*FM (CTN)*	55	12.07	76.94	3.14
TH	*SM (P)*	22	3.13	9.33	0.00
TH	*FM (P)*	N/A	N/A	N/A	N/A
FC	*SM (CTN)*	23	4.81	11.91	2.32
FC	*FM (CTN)*	156	4.87	11.76	1.94
FC	*SM (P)*	7	2.73	4.23	1.16
FC	*FM (P)*	20	5.20	13.44	0.97

Table 12 Comparison of CO_2 emissions in chipping operations, according to different management approaches (*P* – Plantation, *CTN* – Close-to-nature)

	Observations	Average	Max.	Min.
	N	kg CO_2 m^{-3}		
CTN	6	9.70	14.20	5.24
P	13	5.36	11.94	1.66

Table 13 Comparison of CO_2 emissions in secondary haulage, according to different transported material (woodchips or timber). Values derived from unitary values of kg CO_2 m^3 km^{-1} referred to a transportation distance of 100 km (50 km load, 50 km unload)

	Observations	Average	Max.	Min.
	N	kg CO_2 m^{-3}		
Woodchips	30	11.50	47.62	3.17
Timber	8	7.04	17.40	3.03

However chipping is usually a highly energy demanding operation (Pan et al. 2008, Valente et al. 2011), and fuel consumption depends on the size and type of the material to be chipped as well as on the wood density (Van Belle 2006, Röser et al. 2012, Spinelli et al. 2013, Spinelli and Magagnotti 2013). Regarding different types of chippers, it is widely recognized that disc chippers produce more uniform woodchips than drum chippers, especially if fed with good quality raw material. In contrast, flexible small branches may pass through the disc slots uncomminuted, resulting in low chip quality (Spinelli and Hartsough 2001b). Also, dealing with smaller chippers, the disc chipper has higher energy efficiency, using less fuel per unit of product. This may be due to its simpler design, which integrates comminuting and discharge systems into one synergic device. In contrast, the drum chipper is more productive, since it cuts with the same energy along the length of its knives. They, however, produce finer particles (Spinelli et al. 2013).

3.1.3 Secondary transport

As mentioned above, transport generally represents the highest degree of emissions both in timber and energy wood chains (Karjalainen and Asikainen 1996, Schwaiger and Schlamadinger 1998, Schwaiger and Zimmer 2001, Berg and Karjalainen 2003, Berg and Lindholm 2005, Pan et al. 2008, Picchio et al. 2009, England et al. 2013). The only exception was found in Spain (Dias et al. 2007, Gonzalez-Garcia et al. 2009a, Gonzalez-Garcia et al. 2009b), where harvesting emissions are higher than those of the secondary transport.

The main factor affecting fuel consumption in transport is the distance travelled (Schwaiger and Zimmer 2001, Holzleitner et al. 2011, Devlin et al. 2013). Besides distance, the amount of uphill road travel and road condition as well as road design can influence levels of emissions (Pan et al. 2008, Holzleitner et al. 2011). In fact, higher fuel consumption for driving empty was observed because empty trucks usually run uphill. Moreover, lower values for fuel consumption were related to a reduction of travelling on forest roads (Holzleitner et al. 2011). Chip transportation causes higher fuel consumption compared to round wood because of its lower bulk density (Whittaker et al. 2011).

Table 13 reports the values of CO_2 emission in timber and woodchips transportation. Average values of 11.50 kg CO_2 m^{-3} and 7.04 kg CO_2 m^{-3} were calculated, respectively, for woodchips and timber transport over a distance of 100 km (50 km load + 50 km unload).

4. Discussion

Regarding exhaust emissions, it is accepted that substituting conventional fuels with biofuels can reduce gas pollution on a large scale. For example, by using Rapeseed Methyl Ester (*RME*), as much as 6.8 kg CO_2 m^{-3} of CO_2 emissions are reduced compared to using Diesel fuel (Gonzalez-Garcia et al. 2009a, Gonzalez-Garcia et al. 2009b, Klvač and Skoupý 2009).

In addition, CO_2 emissions per cubic meter depend on the level of machine maintenance. In fact, the maintenance shortage affects negatively the productivity by increasing the time lost on repairs (Senturk et al. 2007, Gerasimov et al. 2012, Röser et al. 2012, Spinelli and Magagnotti 2013). In fact, when maintenance is neglected, a lower machine performance and a higher number of delays due to repair time can be expected. As a consequence, productivity decreases and fuel consumption increases. Senturk et al. (2007) suggests that an adequate number of spare parts should be maintained in order to prevent any loss of time in case of urgent maintenance or repair works. Moreover, operator's training, expertise and attitude play a fundamental role in reducing fuel consumption and thus emission as reported by Nordfjell et al. (2003), Kärhä et al. (2004), Kärhä and Vartiamäki (2006), Mederski (2006) and Alam et al. (2014). Finally, a rational harvest planning is essential in maintaining high productivity levels, meaning a higher efficiency in terms of fuel consumption and emissions.

More specific features can be considered regarding harvesting, especially relating to the felling and extraction phases. In either *CTN* or *P* approaches with a *FM* or *SM*, harvesting operations can be achieved by *FT* (Full tree) or *CTL* (Cut-to-Length) work systems. *CTL* is common where trees are motor-manually or mechanically felled, delimbed as well as crosscut at the felling site, and then extracted. Contrarily, in *FT* systems, trees are felled and extracted to the landing area where they are delimbed and crosscut.

In order to understand the advantages of each system, the strength sand weaknesses of the main unique machines in various working conditions are discussed.

4.1 Felling

4.1.1 Chain saw

Knechtle (1997) and Berg (1997) have observed that motor-manual felling gives rise to lower emissions per unit of wood than mechanized felling. For Swedish forestry, the magnitude of the difference between felling methods is so great that even the deployment of resources for transport personnel between home and work sites or between work sites is not sufficient to balance this difference (Berg 1997). Nevertheless, harvesters are fourfold more efficient than a chainsaw, producing less exhaust emissions per kW. This results in a better ecological performance (Lijewski et al. 2013). On the other hand, it has also been recognized that *SM* harvesting systems produce higher emissions in the extraction phase, since forwarding productivity is influenced by the number and the size of the loads (Laitila et al. 2007, Laina et al. 2013). Beside these aspects, manual felling remains a lower cost solution (Laina et al. 2013), but ergonomically marginal (Laina et al. 2013, Lijewski et al. 2013).

4.1.2 Harvester

In many studies carried out on different site conditions, tree volume is the most important factor affecting harvester productivity (hence consumption and emissions) (Sirén and Aaltio 2003, Kärhä et al. 2004, Jiroušek et al. 2007, Laina et al. 2013). CO_2 emissions end up as a tradeoff between the power of machines and the size of trees to be harvested. For example, larger harvesters use more energy, but when processing large trees the energy used is lower than with smaller machines processing small trees (Berg and Lindholm 2005, Klvač and Skoupý 2009). It would appear that smaller harvesters (up to 80 kW), including a tractor with a processor, can operate with the same productivity level as medium-sized harvesters (80–120 kW) in the thinning process. Consequently, they can be run at a fuel consumption and cutting cost lower than those of medium-sized harvesters (Kärhä et al. 2004).

With regard to the work method, in *P* management approach, the use of a cutting-area between two strip-roads was the most efficient working method in thinning using harvesters with short booms (<8 m), even if more damages might occur. Correspondingly, the strip-road method (without cutting-strips) was most efficient when working with harvesters with long booms, although the distribution of the remaining trees is not so even (Kärhä et al. 2004). In thinning operations in stands of Scots pine managed by *CTN* management approach, the midfield operation technique (i.e. harvester is combined with the chain saw in areas that cannot be reached by the harvester between the two skid-roads) was always more productive and much less fuel costly than skid-road one (Mederski 2006).

4.1.3 Harwarder

In an effort to make thinning operations affordable for mechanized processes, the harwarder has appeared as a possible solution. In this case, tree size, removals per hectare and number of timber assortments are the factors affecting productivity when the forwarding distance is limited to 250 m (Wester and Eliasson 2003). Harwarders are most competitive when two timber assortments are applied in small stands (stem volume <0.1 m^3) with short forwarding distance (<250 m) (Sirén and Aaltio 2003). Another possible solution is to fit a feller-buncher head to the forwarder, but studies have found that tree volumes should not be less than 0.05 m^3 (Gingras 2004, Rottensteiner et al. 2008).

4.2 Primary transport

4.2.1 Forwarder

Haulage distance and payload are the ariables affecting forwarder productivity and fuel consumption (Nordfjell et al. 2003, Tiernan et al. 2004, Jiroušek et al. 2007, Laitila et al. 2007). Considering payload, there are no significant differences in fuel consumption when driving loaded or unloaded. However, consumption per unit volume of wood is greater in transporting pulpwood than sawlogs. This is due to longer loading times and smaller volumes of pulpwood, which decreases productivity and increases consumption (Nordfjell et al. 2003). Moreover, when extracting both pulpwood and sawlogs, a two-pass forwarding technique is more productive than a mixed-load forwarding technique (Kellogg and Bettinger 1994).

With regards to site conditions, slope appears to be dramatically significant. Uphill extraction can reduce productivity by 1–5 m^3 PMH$_0^{-1}$ with an obvious increase in fuel consumption. In easy site conditions (gentle slope <10% and even roughness), forwarder productivity is significantly higher in clear-felling sites when compared to thinning sites (2.0 m^3 PMH$_0^{-1}$). In addition, productivity of forwarders with a 10 m boom is up to 9 m^3 PMH$_0^{-1}$ greater than that of forwarders with a 7 m boom (Tiernan et al. 2004).

The main advantages of forwarders over skidders include: less soil disturbance and damages; enhanced work safety and ergonomics; longer extraction distances (hence, reduced road density requirements); less labor; and finally, reduced landing area requirements for handling short wood (Kellogg and Bettinger 1994, Tiernan et al. 2004). The same advantages can be seen when comparing forwarders to tractors with trailers (Spinelli et al. 2012b) notwithstanding larger volumes extracted per cycle. Nevertheless, forwarding with tractors with trailers can offer a technical benefit in terms of higher travel speeds in many small scale forestry harvesting operations (Magagnotti et al. 2013b).

4.2.2 Skidder

Grapple and cable skidders (in steeper terrain) are usually used in clear cutting operations. In fact, their relatively large size makes them more effective in working in the open. Field-measured productivity results are significantly different between cable (43.9±7.5 m^3 PMH$_0^{-1}$) and grapple skidders (123.9±3.9 m^3 PMH$_0^{-1}$), but no difference has been recorded between unloaded and loaded travel speeds (Ackerman et al. 2014).

In similar conditions (Poplar or Eucalyptus plantations), substituting a skidder with an articulated front-end loader could offer a better solution for flail chipping. Although a loader working in conjunction with a skidder takes more time for essentially every extraction element, during extraction and chipping at landing in fast-growing tree species plantations, it can perform 60% more than the skidder because of its larger payload. The capacities of both the skidder and the loader exceeded the productivities of the flail-chippers, so they had excess time. The loader had enough time to handle the landing work. The skidder grapple and decking blade, however, were less suited to moving residues at the landing, and the skidder did not have much excess time, so a second machine was required for landing duties (Spinelli and Hartsough 2001a).

Instead, in the context of small-scale forestry, other more versatile machines are usually used, such as a tractor with a winch. New mini skidders, when compared with common agricultural tractors or forestry-fitted tractors, are more environmentally friendly in terms of energy inputs and *GHG* emissions during wood extraction operations, both in thinning and final cutting (Vusić et al. 2013). This is the case even when compared to crawler tractors in mountainous conditions (Spinelli et al. 2012a). The analysis of working time indicated that equipping a mini-skidder with a double drum winch is important in high forest thinning, due to the smaller size of trees, while for regeneration cuts in high forests, the double drum winch becomes almost redundant. In terms of productivity, energy inputs and emissions, skidding is negatively influenced by slope (uphill over 15%) (Vusić et al. 2013). Finally, in forests with protective rather than productive purpose, All Terrain Vehicle (*ATV*) are an optimal solution for full-tree bunching and skidding operations (<200 m) in first thinning and coppice harvesting since they cause negligible impacts on the ground (i.e. no effect on the roots), and they are able to work on slopes up to 50% (Savelli et al. 2010).

4.2.3 Cable Crane

Aerial cable crane extraction systems are applied in mountainous regions, contributing to better quality of the logs extracted, lower damages to the harvesting site and a reduced necessity for forest roads (Ozturk and Demir 2007, Senturk et al. 2007, Valente et al. 2011). Aerial systems can reduce the energy required per functional unit considerably when compared with fully mechanized systems (Klvač et al. 2012) or with other traditional systems, such as the short-wood-system (*SWS*) in alpine regions (Dias et al. 2007). The productivity of cable cranes is effectively influenced by lateral outhaul, inhaul and in lateral phases (Senturk et al. 2007). In particular, productivity decreases with an increasing number of bundles and with higher extraction distances (Zimbalatti and Proto 2009).

4.2.4 Animal

Animal (horses, mules or oxen) log extraction systems, apart from being the most environmentally friendly solution, show the lowest emissions (Engel et al. 2012, Cerutti et al. 2014). In specific conditions, they can also be competitive in terms of productivity and costs (Magagnotti and Spinelli 2011, Cerutti et al. 2014). Draught horses represent an efficient log extraction tool in steep terrain and in low-intensity cuts, as generally offered by closed canopy forests. Horse skidding incurs lower unit costs than tractor skidding when the extraction distance is short or when skid trails are not available. The cost-efficiency of horse skidding increases significantly when two horses are paired per driver (Magagnotti and Spinelli 2011).

4.3 Integrated harvesting

Integrated harvesting has been developed during last decades with the growing importance of forest residues for energy use in heating and combined heat and power (*CHP*) plants (Friso et al. 2011). Comparisons between conventional product and integrated fuel wood production harvesting in Canada suggests that production costs are highly variable depending on the harvesting system used and the ratio of conventional products to fuel wood (Puttock 1995). The same was seen in a poplar plantation in Italy where a more integrated pulp and chip strategy generally created higher revenues than the exclusive production of woodchips (Spinelli and Magagnotti 2011). However, the additional woodchips produced are generally not the result of potential (i.e. harvesting residues, wood from thinning, coppice stands and short rotation forests), but more a matter of economic feasibility.

Harvesting conditions, roadside landing capacities, road transportation distances, operating volumes and storage capacities of heating and *CHP* plants, availability of production machinery, type of forest woodchips produced and, notably, the total supply chain costs all influence the selection of the forest chip supply chain (Kärhä 2011). Most likely, chipping will move from roadside locations closer to the heating and power plants since the closer plant chipping is performed to their processing destination, the more cost-efficient is the process (Kärhä 2011). Increasing fuel demand will result in a larger supply area for the energy producer and lead to increasing transportation costs. The analysis of different chip production systems resulted in the identification of two major challenges: firstly, the design of the chipping and transport interface, and secondly, the need to reduce transportation costs. Through drying the material, compressing harvesting residues as well as increasing payloads an improved utilization of load volumes can be achieved. For example, drying wood in storage areas near the forest enhances the transportation productivity by 50%. Similarly, bundling harvesting residues pays off, especially for longer transportation distances (Stampfer and Kanzian 2006).

Still, in harvesting agro-forestry plantations, the removal of stumps can be accomplished by two different approaches: grinding or extraction. Results of a study suggested that the use of a stump grinder instead of a stump extractor or backhoe excavator is particularly advisable in terms of productivity, costs and energy inputs (Lindholm et al. 2010). Particularly in the latter case, direct inputs are much higher than indirect inputs. Moreover, stumps extraction negatively contributes to the accumulation of carbon in the agro-forestry soils (Picchio et al. 2012).

Also, slash bundlers are capable of increasing the productivity of both transport and chipping of forest residues as they collect branches in pressed and tight bundles. The amount of residue available on the unit surface, its average size and its distribution on the field are the three main parameters that most affect bundling productivity and fuel consumption (Cuchet et al. 2004). Productivity is considerable if the piles are stacked on both sides of the strip road (Kärhä and Vartiamäki 2006).

4.4 Secondary transport

There are several ways of decreasing energy demands in wood secondary road transport, such as reducing transport distance, adjusting load factors, designing better route-planning systems, improving roads (curve geometry and surfaces), adopting more fuel-efficient driving techniques and using the best available transport carriers (Berg and Lindholm 2005, González-García et al. 2009a, Holzleitner et al. 2011, Pierobon et al. 2015).

5. Conclusion

Despite the small number of papers related to the direct measurement of forest operation emissions, the study provides an effective approach for data and information collection in the field. In particular, it defines a first overview of the carbon emissions from forest operations that encompasses a variety of operative contexts from different countries. Even if the collected information are limited, they are useful in providing some concepts of the level of emissions that can be expected under certain conditions with certain machines in selected harvesting systems. It should be noted that the more detail is required, the greater the risk that specific variables from one study may bias the results. This is particularly true when dealing with harvesting operations, where many variables are involved. However, despite specific cases, there are some important general principles that can be recognized in order to enforce more environmentally friendly harvesting practices that would reduce CO_2 emissions.

Results comparing forestry harvesting, primary transport and chipping show a higher efficiency in *P* management approaches compared to *CTN* management approaches. Secondary transport CO_2 emissions are more affected by the type of product transported, with a higher efficiency for logs compared to woodchips.

Impacts from fully mechanized or semi-mechanized operations can have different patterns according to specific site conditions.

CO_2 emissions in forestry can be reduced at different operative levels, starting by:

- ⇒ Using the most environmentally friendly technologies (e.g. Tier 4 Diesel engines);
- ⇒ Substituting pure Diesel fuel with Diesel-biofuel blends as far as possible;
- ⇒ Maximizing machine productivity and reducing maintenance delays for the proper application of machine maintenance;

Applying the best harvesting plan according to site conditions, forest management, machines features and drawbacks.

With particular regard to this last point, and keeping in mind the high dependence of emissions for both primary and secondary transport on the type and slope of planned routes, it is necessary to underline the importance of using GIS tools to improve the environmental aspects of management logistics. This is particularly important in terms of road networks, which play a fundamental role in operation plan decision making (Cavalli and Grigolato 2010).

Even if the *P* management approach results in lower emissions for felling and chipping operations, the present study does not consider the phases of site preparation and stand tending, which indeed, have a high environmental impact. This may result in a higher global impact for *P* management approaches when compared to *CTN* management approaches in terms of kg CO_2 m^{-3}. Nevertheless, restricted access to natural forests is making plantation forestry increasingly important as a source of wood (Spinelli and Hartsough 2001a).

While *GHG* emissions are evidently a pressing issue, the research conducted here was subject to many shortcomings, due to a high diversity in the coefficients and methodology used by researchers and the technological evolution of engines during the analyzed period. Besides *LCA* studies, for which drawbacks, weak points and proposals for improvement have already been highlighted by Heinimann et al. (2012), in all other cases a more standardized manner for collecting productivity, fuel consumption and *GHG* emissions data should be developed. This would ensure the comparability of results and the repeatability of experiments, both fundamental elements of the scientific method.

Proposals for the development and harmonization of new operational research and assessment procedures for *GHG* emissions should be promoted following an approach similar to procedures adopted by other forestry frameworks/organizations, e.g. in sustainable forest biomass supply in the frame of Cost Action FP-0902 (Magagnotti et al. 2013a).

With reference to the difficulties encountered here, some suggestions to enforce the effectiveness of the scientific forestry literature include:

- ⇒ Defining a homogeneous silviculture terminology for reference purposes;
- ⇒ Reporting values of coefficients necessary to switch from PMH_0 (or SMH_0) to PMH_{15} (or SMH_{15}), or from SMH to PMH, or vice-versa;
- ⇒ Reporting values of coefficients to allow the reader to switch from values for the weight of wood to values for the volume of wood, taking into account its own bulk density and the moisture content.

Acknowledgements

The study was carried out within the framework of the Programme EU FP7 PEOPLE 2011 IRSES, Theme Marie Curie Actions, Project »Climate-fit forests« (GA 295136). We thank Philipp Gloning for the useful comments and suggestions.

6. References

Ackerman, P., Pulkki, R., Gleasure, E., 2014: Modelling of wander ratios, travel speeds and productivity of cable and grapple skidders in softwood sawtimber operations in South Africa. Southern Forests: a Journal of Forest Science 76(2): 101–110.

AGQM, 2009: Information zum Gesetz zur Einfuerung einer Biokraftstoffquote durch Aenderung des Bundesimmissionsschutzgesetzes und zur Aenderung energie- und stromsteurrechtilche Vorschriften [Information for law introducing a biofuel quota by amending the Federal Pollution Control Act and amending energy and current tax regulations]. Available at: from http//:www.agqm-biodiesel.de. [Accessed April 5th 2009]

Alam, M., Walsh, D., Strandgard, M., Brown, M., 2014: A log-by-log productivity analysis of two Valmet 475EX harvesters. International Journal of Forest Engineering 25(1): 14–22.

Altın, R., Cetinkaya, S., Yücesu, H.S., 2001: The potential of using vegetable oil fuels as fuel for diesel engines. Energy Conversion and Management 42(5): 529–538.

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

Athanassiadis, D., Lidestav, G., Nordfjell, T., 2002: Energy use and emissions due to the manufacture of a forwarder. Resources, Conservation and Recycling 34(3): 149–160.

Bailey, A.P., Basford, W.D., Penlington, N., Park, J.R., Keatinge, J.D.H., Rehman, T., Tranter, R.B., Yates, C.M., 2003: A comparison of energy use in conventional and integrated arable farming systems in the UK. Agriculture, Ecosystems & Environment 97(1–3): 241–253.

Berg, S., 1995: The environmental load of fossil fuels in Swedish forestry-an inventory for a LCA. Proceeding of the Life-Cycle Analysis – A challenge for forestry and forestry industry. European Forest Institute, Hamburg, Germany, 3–5 May, 57–65.

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

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

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

Cavalli, R., Grigolato, S., 2010: Influence of characteristics and extension of a forest road network on the supply cost of forest woodchips. Journal of Forest Research 15(3): 202–209.

Cerutti, A.K., Calvo, A., Bruun, S., 2014: Comparison of the environmental performance of light mechanization and animal traction using a modular LCA approach. Journal of Cleaner Production 64: 396–403.

Cuchet, E., Roux, P., Spinelli, R., 2004: Performance of a logging residue bundler in the temperate forests of France. Biomass and Bioenergy 27(1): 31–39.

CWAPE, 2002: Coefficients d'émission de CO_2 de différentes sources d'énergie primarie [CO_2 emission coefficients for different primary energy resources]. Comité de Direction: 03 Décembre 2002. Commision Wallonne pour l'Energie, Namure (Belgrade), 9 p.

Devlin, G., Klvac, R., McDonnell, K., 2013: Fuel efficiency and CO_2 emissions of biomass based haulage in Ireland – A case study. Energy 54: 55–62.

Dias, A. C., Arroja, L., Capela, I., 2007: Carbon dioxide emissions from forest operations in Portuguese eucalypt and maritime pine stands. Scandinavian Journal of Forest Research 22(5): 422–432.

Dixon, R.K., Solomon, A.M., Brown, S., Houghton, R.A., Trexier, M.C., Wisniewski, J., 1994: Carbon Pools and Flux of Global Forest Ecosystems. Science 263(5144): 185–190.

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

England, J.R., May, B., Raison, R.J., Paul, K.I., 2013: Cradle-to-gate inventory of wood production from Australian softwood plantations and native hardwood forests: Carbon sequestration and greenhouse gas emissions. Forest Ecology and Management 302: 295–307.

EPA, 2008: Direct Emissions from Mobile Combustion Sources. EPA – United States Environmental Protection Agency Climate Leaders, Washington DC, 31 p.

EU, 2014: A policy framework for climate and energy in the period from 2020 to 2030. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Region: COM/2014/0015. European Union, Brussels, 18 p.

FAO, 1992: Cost Control in Forest Harvesting and Road Construction. FAO Forestry Paper: 99. Food and Agriculture Organization of the United Nations, Rome, 106 p.

Freitas, C., 2004: Análise dos encargos horários com a utilização das máquinas pesadas na agricultura e floresta. IHERA – Gabinete de Gestão do Parque de Máquinas, Direcção de Serviços de Projectos e Obras, Instituto de Desenvolvimento Rural e Hidráulica, Lisboa, 13 p.

Friso, D., Grigolato, S., Cavalli, R., 2011: Energetic and exergetic analysis of steam production for the extraction of coniferous essential oils. Biomass and Bioenergy 35(9): 4045–4056.

Furuholt, E., 1995: Life cycle assessment of gasoline and diesel. Resources, Conservation and Recycling 14(3): 251–263.

Gerasimov, Y., Seliverstov, A., Syunev, V., 2012: Industrial round-wood damage and operational efficiency losses associated with the maintenance of a single-grip harvester head model: a case study in Russia. Forests 3(4): 864–880.

Gillenwater, M., 2005: Calculation Tool for Direct Emissions from Stationary Combustion. World Resources Institute, Washington DC, 94 p.

Gingras, J.F., 2004: Early studies of multi-tree handling in Eastern Canada. International Journal of Forest Engineering 15(2): 18–22.

González-García, S., Bacenetti, J., Murphy, R.J., Fiala, M., 2012: Present and future environmental impact of poplar cultivation in the Po Valley (Italy) under different crop management systems. Journal of Cleaner Production 26: 56–66.

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

Gonzalez-Garcia, S., Berg, S., Moreira, M.T., Feijoo, G., 2009b: Evaluation of forest operations in Spanish eucalypt plantations under a life cycle assessment perspective. Scandinavian Journal of Forest Research 24(2): 160–172.

Grägg, K., 1999: Emissions from two truck engines and two off-road engines. MTC: 6806. AB Svensk Bilprovning Motortestcenter, Haninge, 14 p.

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

Holzleitner, F., Kanzian, C., Stampfer, K., 2011: Analyzing time and fuel consumption in road transport of round wood with an onboard fleet manager. European Journal of Forest Research 130(2): 293—301.

IPCC, 1993: Greenhouse Gas Inventory Reference Manual. First Draft. US Enviromental Protection Agency, Washington, 360 p.

IPCC, 2006: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and other Land Use. National Greenhouse Gas Inventories Programme, Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Cambridge (First ed.). Cambridge University Press, 996 p.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007: How strongly can forest management influence soil carbon sequestration? Geoderma 137(3–4): 253–268.

Jiroušek, R., Klvač, R., Skoupý, A., 2007: Productivity and costs of the mechanised cut-to-length wood harvesting system in clear-felling operations. Journal of Forest Science 53(10): 476–482.

Kärhä, K., 2011: Industrial supply chains and production machinery of forest chips in Finland. Biomass and Bioenergy 35(8): 3404–3413.

Kärhä, K., Rönkkö, E., Gumse, S.I., 2004: Productivity and Cutting Costs of Thinning Harvesters. International Journal of Forest Engineering 15(2): 43–56.

Kärhä, K., Vartiamäki, T., 2006: Productivity and costs of slash bundling in Nordic conditions. Biomass and Bioenergy 30(12): 1043–1052.

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

Kellogg, L.D., Bettinger, P., 1994: Thinning Productivity and Cost for a Mechanized Cut-to-Length System in the Northwest Pacific Coast Region of the USA. Journal of Forest Engineering 5(2): 43–54.

Klvač, R., Fischer, R., Skoupý, A., 2012: Energy Use of and Emissions from the Operation Phase of a Medium Distance Cableway System. Croatian Journal of Forest Engineering 33(1): 79–88.

Klvač, R., Skoupý, A., 2009: Characteristic fuel consumption and exhaust emissions in fully mechanized logging operations. Journal of Forest Research 14(6): 328–334.

Klvač, R., Ward, S., Owende, P.M.O., Lyons, J., 2003: Energy audit of wood harvesting systems. Scandinavian Journal of Forest Research 18(2): 176–183.

Knechtle, N., 1997: Materialprofile von Holzerntesystemen–Analyse ausgewählter Beispiele als Grundlage für ein forsttechnisches Ökoinventar [Material profiles from forest harvest systems. Analyses of chosen examples as a base for forest LCI]. Departement Wald- und Holzforschung, ETH, Zürich, 65 p.

Korpilahti, A., 1998: Finnish forest energy systems and CO_2 consequences. Biomass and Bioenergy 15(4–5): 293–297.

Laina, R., Tolosana, E., Ambrosio, Y., 2013: Productivity and cost of biomass harvesting for energy production in coppice natural stands of *Quercus pyrenaica* Willd. in central Spain. Biomass and Bioenergy 56: 221–229.

Laitila, J., Asikainen, A., Nuutinen, Y., 2007: Forwarding of Whole Trees After Manual and Mechanized Felling Bunching in Pre-Commercial Thinnings. International Journal of Forest Engineering 18(2): 29–39.

Landa, A.H., Szabo, I., Le Brun, L., Owen, I., Fletcher, G., Hill, M., 2011: An evidence-based approach to scoping reviews. The Electronic Journal of Information Systems Evaluation 10(4): 173–175.

Lloyd, A.C, Cackette, T.A., 2001: Diesel Engines: Environmental Impact and Control. Journal of the Air & Waste Management Association 51(6): 809–847.

Lijewski, P., Merkisz, J., Fuć, P., 2013: Research of exhaust emissions from a harvester diesel engine with the use of portable emission measurement system. Croatian Journal of Forest Engineering 34(1): 113–122.

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

Liška, S., Safarik, D., Klvač, R., Kupcak, V., Jirousek, R., 2010: General assessment of Jenz Hem 420 D chipper operating in the Czech Republic conditions. Proceeding of the FORMEC 2010 – Forest Engineering: Meeting the Needs of the Society and the Environment. CLEUP, Padova, July 11–14, 8 p.

Liski, J., Pussinen, A., Pingoud, K., Mäkipää, R., Karjalainen, T., 2001: Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research 31(11): 2004–2013.

Magagnotti, N., Kanzian, C., Schulmeyer, F., Spinelli, R., 2013a: A new guide for work studies in forestry. International Journal of Forest Engineering 24(3): 249–253.

Magagnotti, N., Picchi, G., Spinelli, R., 2013b: A versatile machine system for salvaging small-scale forest windthrow. Biosystems Engineering 115(4): 381–388.

Magagnotti, N., Spinelli, R., 2011: Financial and energy cost of low-impact wood extraction in environmentally sensitive areas. Ecological Engineering 37(4): 601–606.

McDonnell, K., Ward, S., Leahy, J. J., McNulty, P., 1999: Properties of rapeseed oil for use as a diesel fuel extender. Journal of the American Oil Chemists' Society 76(5): 539–543.

Mederski, P. S., 2006: A comparison of harvesting productivity and costs in thinning operations with and without midfield. Forest Ecology and Management 224(3): 286–296.

Nordfjell, T., Athanassiadis, D., Talbot, B., 2003: Fuel consumption in forwarders. International Journal of Forest Engineering 14(2): 11–20.

Normand, X., Treil, A., 1985: L'Industrie Du Raffinage Du Petrole: Lecons sommaires. Institut Français du Pétrole, Paris, 363 p.

Öko-Institut, 2008: Global Emission Model for Integrated Systems (GEMIS) – Version 4.5. Darmstadt.

Ozturk, T., Demir, M., 2007: Transporting of spruce timbers by URUS MIII cable system from selective forests of Artvin region. Building and Environment 42(3): 1278–1282.

Pan, F., Han, H.S., Johnson, L.R., Elliot, W.J., 2008: Net energy output from harvesting small-diameter trees using a mechanized system. Forest products journal 58(1–2): 25–30.

Perry, R. H., Green, D. W., 1997: Perry's Chemical Engineers' Handbook. New York (7th ed.). McGraw-Hill., 2640 p.

Picchio, R., Maesano, M., Savelli, S., Marchi, E., 2009: Productivity and energy balance in conversion of a *Quercus cerris* L. coppice stand into high forest in Central Italy. Croatian Journal of Forest Engineering 30(1): 15–26.

Picchio, R., Verani, S., Sperandio, G., Spina, R., Marchi, E., 2012: Stump grinding on a poplar plantation: Working time, productivity, and economic and energetic inputs. Ecological Engineering 40: 117–120.

Pierobon, F., Zanetti, M., Grigolato, S., Sgarbossa, A., Anfodillo, T., Cavalli, R., 2015. Life cycle environmental impact of firewood production – A case study in Italy. Applied Energy 150: 185–195.

Puttock, G.D., 1995: Estimating cost for integrated harvesting and related forest management activities. Biomass and Bioenergy 8(2): 73–79.

Röser, D., Mola-Yudego, B., Prinz, R., Emer, B., Sikanen, L., 2012: Chipping operations and efficiency in different operational environments. Silva Fennica 46(2): 275–286.

Rottensteiner, C., Affenzeller, G., Stampfer, K., 2008: Evaluation of the Feller-Buncher Moipu 400E for Energy Wood Harvesting. Croatian Journal of Forest Engineering 29(2): 117–128.

Routa, J., Kellomäki, S., Kilpeläinen, A., Peltola, H., Strandman, H., 2011: Effects of forest management on the carbon dioxide emissions of wood energy in integrated production of timber and energy biomass. GCB Bioenergy 3(6): 483–497.

Routa, J., Kellomäki, S., Peltola, H., 2012: Impacts of Intensive Management and Landscape Structure on Timber and Energy Wood Production and net CO_2 Emissions from Energy Wood Use of Norway Spruce. BioEnergy Research 5(1): 106–123.

Savelli, S., Cavalli, R., Baldini, S., Picchio, R., 2010: Small scale mechanization of thinning in artificial coniferous plantation. Croatian Journal of Forest Engineering 31(1): 11–21.

Schwaiger, H., Schlamadinger, B., 1998: The potential of fuelwood to reduce greenhouse gas emissions in Europe. Biomass and Bioenergy 15(4): 369–377.

Schwaiger, H., Zimmer, B., 2001: A comparison of fuel consumption and greenhouse gas emissions from forest operations in Europe. Energy, Carbon and Other Material Flows in the Life Cycle Assessment of Forestry and Forest Products. Joensuu, European Forest Institute, 33–53.

SEA, 2008: Energy indicators 2008 Theme: Renewable Energy. Kungsgatan, Swedish Energy Agency (SEA), 21 p.

Senturk, N., Ozturk, T., Demir, M., 2007: Productivity and costs in the course of timber transportation with the Koller K300 cable system in Turkey. Building and Environment 42(5): 2107–2113.

Sirén, M., Aaltio, H., 2003: Productivity and Costs of Thinning Harvesters and Harvester-Forwarders. International Journal of Forest Engineering 14(1): 39–48.

Spinelli, R., Cavallo, E., Eliasson, L., Facello, A., 2013: Comparing the efficiency of drum and disc chippers. Silva Fennica 47(2): 1–11.

Spinelli, R., Hartsough, B.R., 2001a: Extracting whole short rotation trees with a skidder and a front-end loader. Biomass and Bioenergy 21(6): 425–431.

Spinelli, R., Hartsough, B.R., 2001b: A survey of Italian chipping operations. Biomass and Bioenergy 21(6): 433–444.

Spinelli, R., Magagnotti, N., 2011: Strategies for the processing of tree tops from hybrid poplar plantations. Baltic Forestry 17(1): 50–57.

Spinelli, R., Magagnotti, N., 2013: Performance of a small-scale chipper for professional rural contractors. Forest Science and Practice 15(3): 206–213.

Spinelli, R., Magagnotti, N., Laina Relaño, R., 2012a: An alternative skidding technology to the current use of crawler tractors in Alpine logging operations. Journal of Cleaner Production 31: 73–79.

Spinelli, R., Schweier, J., De Francesco, F., 2012b: Harvesting techniques for non-industrial biomass plantations. Biosystems Engineering 113(4): 319–324.

Stampfer, K., Kanzian, C., 2006: Current state and development possibilities of wood chip supply chains in Austria. Croatian Journal of Forest Engineering 27(2): 135–145.

Tiernan, D., Zeleke, G., Owende, P.M.O., Kanali, C.L., Lyons, J., Ward, S.M., 2004: Effect of Working Conditions on Forwarder Productivity in Cut-to-length Timber Harvesting on Sensitive Forest Sites in Ireland. Biosystems Engineering 87(2): 167–177.

Valente, C., Spinelli, R., Hillring, B.G., 2011: LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). Journal of Cleaner Production 19(17–18): 1931–1938.

Van Belle, J.F., 2006: A model to estimate fossil CO_2 emissions during the harvesting of forest residues for energy-with an application on the case of chipping. Biomass and Bioenergy 30(12): 1067–1075.

Vusić, D., Šušnjar, M., Marchi, E., Spina, R., Zečić, T., Picchio, R., 2013: Skidding operations in thinning and shelterwood cut of mixed stands – Work productivity, energy inputs and emissions. Ecological Engineering 61: 216–223.

Wester, F., Eliasson, L., 2013: Productivity in final felling and thinning for a combined harvester-forwarder (Harwarder). International Journal of Forest Engineering 14(2): 45–51.

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

Wolf,C., Klein, D., Weber-Blaschke, G., Richter, K., 2015: Systematic Review and Meta-Analysis of Life Cycle Assessments for Wood Energy Services. Journal of Industrial Ecology. Article in press, DOI: 10.1111/jiec.12321

Zimbalatti, G., Proto, A.R., 2009: Cable logging opportunities for firewood in Calabrian forests. Biosystems Engineering 102(1): 63–68.

Zorić, M., Šušnjar, M., Pandur, Z., Mihaljević, K., 2014: Fuel Consumption and Greenhouse Gas Emission in Timber Haulage in Croatian Forestry. Nova mehanizacija šumarstva 35(1): 89–97.

Received: February 10, 2015
Accepted: October 13, 2015

Authors' addresses:

Giulio Cosola, MSc.
e-mail: giulio.cosola@gmail.com
Prof. Stefano Grigolato, PhD.
e-mail: stefano.grigolato@unipd.it
Sergio Monterotti, MSc.
e-mail: sergio.monterotti@gmail.com
Prof. Raffaele Cavalli, PhD.*
e-mail: raffaele.cavalli@unipd.it
Dept TESAF – University of Padova
Viale dell'Università 16
35020 Legnaro
ITALY

Prof. Pierre Ackerman, PhD.
e-mail: packer@sun.ac.za
Dept of Forest and Wood Science
Stellenbosch University
Private Bag X1
Matieland, 7602
Stellenbosch
SOUTH AFRICA

* Corresponding author