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LIFE CYCLE INVENTORY OF TIMBER HARVESTING BY FOREST MACHINERY

Master thesis

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ABSTRACT

Information about environmental impacts of forest machines is wide and very specific. Lots of publications and articles paired with technical files and data sheets are available for all machines that have been produced in the last years. Having an overview over this broad topic is hard and sometimes information overlaps or doesn’t even match with the requirements. Life Cycle Inventory (LCI) is gaining importance as further requests by international regulation and by an increasing self-consciousness by the forest enterprises. LCI is the data collection portion of life cycle assessment (LCA). LCI is the straight-forward accounting of everything involved in the “system” of interest. It consists of detailed tracking of all the processes and related flows in and out of the product system. The objective of this thesis is to concentrate and sum up all the information that can be found regarding environmental impacts of timber harvesting and transport processes.

All the information has been gathered looking through publications, articles, technical files. The outcomes of this work are, as anticipated listing the objectives, a document that summons all the information regarding different machines, taking into consideration also site conditions and external factors that could have influenced the outcomes. A total of 173 publications has been analysed, after that all machines’ performances have been separately listed in different excel sheets and after that all the data normalized. The machines that were researched where chainsaws, harvesters, harwarders, cable yarders, excavator, forwarders, loaders, skidders, slash bundlers, chippers, tractors and trucks. It resulted that the most studied machine was the harvester, followed by the forwarder and the two least ones were loaders and slash bundlers.

Statistical analysis was held to provide a complete overview of the data. Descriptive statistic was done as well as highlighting possible future trends and describing linear models. To make it handier an appendix with all the data for every machine taken into consideration was added to this work.

1 INTRODUCTION

1.1 Problem statement

Forests have always been used as resources providers and things didn't change today, indeed the withdraws of timber and other goods increased over the past years (FAO, 2016). This phenomenon can be addressed to the higher timber demand being rediscovered as an eco-friendly material. Besides that, the progress helped the timber industry with bigger, more efficient and more technological machines to be up to date. This steady progress, paired with the new environmental requests these processes have (Duka, 2017), lead to a high number of studies, both academic and not, focusing on the machines and their performances (Cosola et al., 2017 and Klein et al., 2015).

Consideration of environmental factors are getting nowadays more important, also in the forestry sector. Data regarding fuel consumption and emission of forest machines are scattered and, in certain cases, missing but on the other side are also gaining importance and are increasing in number as driving factor of the sustainability of the forestry sector.

The main issue related to the topic is the fact that all the studies reporting this kind of data are different from each other, as they have different objectives leading to different measure unit and different collection methods. The type of publication really influences how fuel or emission data were reported and how the publication got them. What triggered this work was initially the lack of a complete and big enough dataset reporting all the information regarding fuel consumption and/or emissions, then the extremely high heterogeneity of the data collected during the first part of this work. Starting from these different aspects of the topic some objectives logically followed up.

1.2 Objectives

The following ones are the objectives that have been selected after analysing the data quality of the database:

- The final objective of this work is to create a database, as complete as possible reporting fuel consumption and emission data for some selected machine involved in forest operations, performing an LCI study as defined by the ISO 14044.

- Descriptive statistic will be implemented on the dataset to highlight the differences between machines and to have a global look for every machine and their specifications.

- A series of models will be derived to express fuel consumption based on the power and/or productivity data of the machines. From these models will be easy to assess also emission data. Firstly, with a single variable then with both variables combined. From these fuel consumption models emission models are obtained with simple conversion factors. This because fuel consumption data are more represented among this type of studies and for this reason the emissions have been derived from the fuel consumption with calculations.

- A general trend in fuel consumption over time for every possible machine will be identified to see if with the technological progress of the machines the performance of them increased making them more fuel efficient.

2 STATE OF THE ART

2.1 Relevance of forests

Forests occupy 25% of the global land cover, for a total of 39 million of square kilometres (FAOSTAT, 2016). Forests are the first source of income for rural people, provide water and are keepers of biodiversity in all its forms and can play a touristic function. But in the last decades the main function of forests was to be the keeper of different resources, such as roundwood, energy and food for a total standing mass of 600 billion of m^3. Europe itself produces and consumes 400 million m^3 of wood products. Resources production is the first function of the global forests, but lately other functions arose making harder to manage forests properly on one hand but on the other hand even more important and crucial for the global society. Forests for recreational purposes and for protection/protective ones are an example of ecosystem services that forest can offer to the society, but forests and their carbon sink's function is an issue with a global effect, more over considering the climate change effects.

It is so important, while dealing with forests and timber production, to operate in a sustainable way to avoid important and irreparable losses to the carbon cycle of which forests are an important actor. In fact, global warming and forestry are strictly related and the latter can be part of the solution for the first one. The IPCC report, in his ninth chapter that's the one focusing on forests, identify forests and its sustainable management as a key factor to fight climate change thanks to the forests' carbon sink ability. The strong points of forestry as a mitigation factor relies on its low-cost aspects and to the fact that forestry can deal with several issues at the same time. Sustainable forest management can, in fact, deal with climate change mitigation, biodiversity maintenance and sustaining rural development. The weakness of forestry, on the other hand are related to the institutional capacity that isn't always sufficient, the RD technology transfer and the capital investment that are often lacking representing a barrier for the development of these good forestry practices.

The IPCC report recognizes deforestation as a major contributor to climate change in the forestry sector and it measures that it causes 5.8 Gt CO_2 eq./year starting from 1990s. It also identifies mitigation and adaptation as major approaches to climate changes. As forestry mitigation activities relies under the Kyoto protocol forest sustainability can be supported by an increased number of activities, simplified procedures and a bunch of other facilitations that must be used in order to reach the final aim, stop climate change (IPCC, 2013).

2.2 Forestry and mechanization

Timber increasing demand brought into the forests some machine necessary to increase the producitivity of timber harvesting (Erber et al., 2007). Due to the last decade increasing attention to GHG and process sustainability (Duka et al., 2007) timber extraction was subsequently involved in this cluster of studies. As there are machine involved in forest mechanization inputs and outputs are the most investigated variables in this field.

Forest operations have always been highly labour intensive but since appearance of mechanized harvesting systems a lot has changed. The forest workers' safety condition and comfort has increased as the total productivity. On the other side manpower demand has decreased (Duka, 2017). This can be translated in higher economic values but also higher impact on the environment and on the site.

Machines involved in forest operations and subsequently in this study are a lot and various accordingly to the operation they have to carry on and the geomorphological aspect of the sites. The main activities that occur in forestry are harvesting, first and second transportation. Felling is usually carried on with chainsaws and harvesters and in some rare cases with harwarders. Often the harvester fells the tree, debranching and cross cutting it. Cable yarders, skidders, forwarders, harwarders and forest tractors are all responsible for the extracting phase and moving timber from the forest to the roadside Other activities are chipping, made with chippers, that can be mobile, truck-mounted or tractor powered. At last loaders, that stack and sort timber, and slash bundlers, that create bundlers with forest residues, are considered forest processing machines. At roadside the logging trucks take over and begin the so-called transportation.

Forest mechanization's levels appears to be strictly related to the area of use. (Bronisz et al., 2018). Different harvesting systems are used in different region of the world as results of topography and social aspects as major constraining factors.

In Europe the heterogeneity of machines used varies a lot and can be identified on a zonal subdivision. In North Europe the main harvesting system is the one composed by harvester and forwarder (approx. 90%) and less often chainsaw and skidder. Central East Europe combine different machines showing a good level of heterogeneity using also chainsaws, skidders and cable yarders. Central West Europe use only chainsaw as main harvesting system, varying the extraction method as forwarder and skidder. South Europe, on the other side, shows an extremely broad range of machine used due to a high variability of topographical aspects (Bronisz et al., 2018). The southern hemisphere is more likely the northern part of Europe as on it relies, mostly, on a combination of harvester and forwarder/skidder for the extraction phase. This appears to be given by the higher share of plantation forestry (i. e. South Africa and Latin America) (Ackerman et al., 2016).

Erber and Kühmaier (2017) identified some more trends in forest mechanizations. The harvesting operations in the last 25 years, and subsequently their related researches, changed a lot and steadily triggered by the new technologies that occurred, demonstrating that the forest mechanization sector is in continuous development, now facing new challenges related to environmental soundness and to ergonomics issues for the forest workers (Marchi et al., 2018).

2.3 Forestry and sustainability

Forestry has always been one of the best sectors regarding environmental and economical sustainability Nowadays the importance of sustainability and environmental impact assessment processes and systems is gaining more and more importance, and it's clearly evident that also forestry sector should step ahead and innovate itself as regarding the impact on the environment that its processes have. The hindering factors are a lot and the general framework is heterogeneous and sometimes overlapping.

Forestry and sustainability in the form of Sustainable Forest Management (SFM) started with the Brundtland report Our Common Future (World Commission on Environment and Development, 1987) setting the foundation for all the successive developments' reports as the 1992's Rio de Janeiro UN conference, followed by the Intergovernmental Panel on Forest and the Intergovernmental Forum on Forests coming to the first years of 2000 (Wang, 2004). Successive reports and conferences helped to identify e define variables and parameters to increase the clarifications, unfortunately to date is still lacking a globally agreed definition of SFM. Nevertheless, SFM is generally intended as the way of managing the forest to meet society's needs in the present and in the future (Wang, 2004). A whole of different acronym are related to SFM and have been used as different approaches:

- Environmentally Sound Forest Harvesting (ESFH)
- Reduced Impact Logging (RIL)
- Forest Operations Ecology (FOE)
- Sustainable Forest Operations (SFO)

These different approaches vary accordingly to scale and focus but they do have the same aim but became outdated and got substituted (Marchi, 2018). Reduced Impact Logging claimed to have lower intensity to reduce the impacts on the environment (Dykstra, 2001), for instance was popular during the 1900s but was outdated by other approaches such as SFO.

A big share of SFM issues is explained by the strong linkage between management and forest operations, for this reason the ground of sustainability is still uneven. Sustainable Forest Operations (SFO), that is the contemporary approach to forest operations, and it differs from the previous ones as it is more complete and involves more aspects compared to other approaches and subsequently more complex. (Marchi et al., 2018)

It relies on five different pillars that are:

- Environment
- Ergonomics
- Economics
- Quality optimization
- People and society

The first pillar, the environmental aspect, aims for a minimization of impacts on the environment and it translates its objective into action due to some focus points such as energy consumption, soil, air, water, biodiversity and remaining stand. The second pillar is the economics one claiming that forest operations should be done in a profitable way in order to sustain the people that relies on these kinds of activities. The ergonomics' pillar states that forest workers should stay in safe conditions while operating. As regards quality optimization should refer to the improvements in the harvesting phase, reducing wastes and enhancing product's quality. People and society's aspect, one the last one introduced and one of the most complex (La Notte, 2017), considers the services that are bound to the forests and subsequently have a social relevance (Marchi et al., 2018).

Climate change is a shift in average global temperature that triggers phenomenon on all scales, sector and forests have been appointed as one of the most effective mitigation measures against climate change. Mitigation and adaptation are two viable approach to climate change and their trade-offs and synergies are most likely to happen due to the complexity and scale of the phenomenon (Klein, 2015). Mitigation act on the long term and is more complex compared to adaptation that, on the other side, suits better plantation forestry rather than any other forestry aspect (IPCC, 2013).

In the fourth IPCC report both mitigation and adaptation's viable options are laid down in a matrix showing also implications and vulnerability of the options. The four main focuses of the abovementioned matrix are:

- Increasing or maintaining forest area
- Changing forest management: increasing carbon density at plot and landscape level
- Substitution of energy intensive materials
- Bioenergy

Even if forest mechanization isn't directly mentioned all the four focus areas are strictly connected with it. For instance, the last point, bioenergy, where woody biomasses play a very important role and machines such as chippers are the only help for this kind of energy.

2.4 LCA and forestry

LCA is one of the several environmental management techniques and is linked with forestry for more than 20 years to date, going back to the 1960's in certain forerunning cases, since it deals with complex processes that create different products as forestry does (Klein et al., 2015). LCA can be used to:

- Identify opportunities to improve environmental performances of
- Support decision makers at all levels
- Support the selection of relevant environmental performances
- Support marketing choices moved by ecological willingness.

The ISO standards have a relevant role in the implementation of the LCA studies as they identified how the importance of environmental protection and the possible impacts has increased the general interests in this matter (ISO 14044). As other important environmental management techniques, the LCA can't be the best management technique for every situation, in particular LCA fails to consider social and economic aspects of a products, e.g. a medicine might have a high impact on the environment but can save lives.

To create a common process in running an LCA on a global scale ISO/EN norms for LCA were developed.

2.4.1 ISO standards

ISO stands for International Organization for Standardizations on a global scale (ISO member bodies) and its aim is to standardize all the processes. The normative framework of the LCA is broad as there are a lot of ISO/EN norms that are related to LCA. Specifically listed as code, year and content:

- ISO 14020: 2000 (Environmental labels and declaration – General Principles)
- ISO 14021: 1999 (Environmental labels and declaration – Self-declared environmental claims, Type II environmental labelling)
- ISO 14024: 1999 (Environmental labels and declaration – Type I environmental labelling – Principles and procedures)
- ISO 14025: 2006 (Environmental labels and declaration – Type III environmental labelling - Principles and procedures)

- ISO 14040: 2006 (Environmental management – Life cycle assessment – Principles and framework)

- ISO 14044: 2006 (Environmental management – Life cycle assessment – Requirements and guidelines)

- ISO/TR 14047: 2003 (Environmental management – Life cycle assessment - Example of application of ISO 14042)

- ISO/TS 14048: 2002 (Environmental management – Life cycle assessment – Data documentation format)

- ISO/TR 14049: 2000 (Environmental management – Life cycle assessment – Examples of application of ISO 14041 to goal and scope definition and inventory analysis) (New versions 2012)

The ones that are mostly involved in this thesis' work are the ISO 14040 and ISO 14044 that includes LCI (Life cycle Inventory) and the general guidelines of the LCA processes (Figure 1). Successive versions exist already as the LCA process is reviewed every 5 years (ISO 14040).

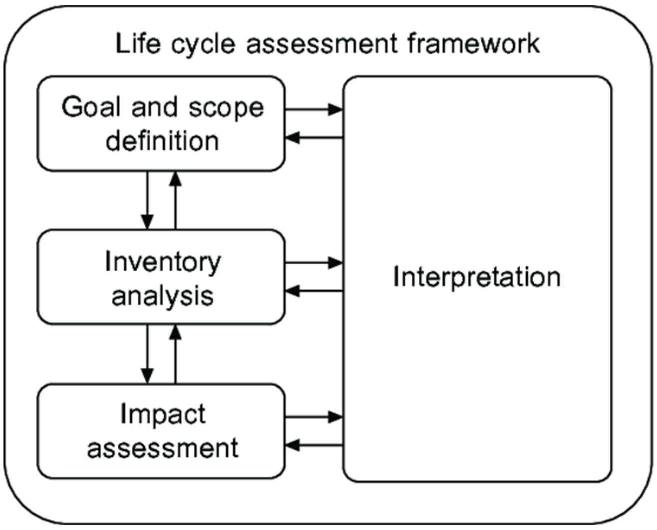

Figure 1 - LCA framework

There are four phases in an LCA study that are:

1. Goal and scope definition

2. Inventory analysis

3. Impact assessment

4. Interpretation

Every phase produces important outcomes for the final objectives. The first phase is responsible for the draft of these objectives in fact. The level of details that this part of the process can have is usually defined at the beginning of the entire process. The second one, the LCI, that stands for "Life Cycle Inventory" is defined as "an inventory of output/input data with regard to the system being studied. It involves the collection of the data necessary to meet the goals of the defined study" (ISO 14044: 2006). The third phase has the purpose to provide additional information to give to the LCI data an environmental significance, translating the inventory data into impact ones, and it's called Life Cycle Impact Assessment (LCIA). The last phase summarizes and discusses the results coming from an LCI and/or LCIA.

2.4.2 Goal and scope definition

As stated in the previous paragraph an LCI study requires a "Goal and Scope". Based on the list of uses wrote in at the beginning of this chapter, this work strives to reach the following goal and scope:

In this work an LCI study will be performed with the scope of producing a fuel consumption and CO_2 emission database based on real life studies and research. This could be used for further researches and impact analysis.

2.4.3 LCA studies in forestry

Deepening the matter of LCA studies and forestry a whole of different tools, approaches, reports and protocols can be enlisted (Klein et al., 2015, Bosner, 2012). Despite Klein et al. (2015) highlight the importance of this kind of studies and their impact some issues come along while performing them in forestry:

- Forestry uses a high amount of land.
- Forest products have a long and complex production cycle, starting from wood production up to disposal or burning for energy. Several steps in between usually occur.
- Forest products have an extremely wide range for life spans (newspaper to structural timber).
- The relationship between main products, by-products and wastes is relatively complex.

Due to his high complexity and due to the fact that forests are part of the ecosystem some scientists reckon that forests should be considered as an impact category. They're strongly influenced by both internal and external factors that have an impact on the carbon stock and fluxes. For this reason, Bosner (2012) states that is crucial to implement a complete LCA studies on forests to have reliable data. Complete, always as reported by Bosner (2012), means that the study considers all the aspects involved and related to the forestry sectors. Not only fluxes, that are the most studied aspect of forest operations, but also on stocks and the hardly-to-measure beneficial aspects.

Another problematic aspect is given by the functional unit. In their study, Klein et al. (2015) surveyed 26 studies and 2 databases and collected a total of 12 different functional units expressed by dimension, area, time and mass. Different functional units are related to different goal and scope but most of the time some crucial aspect, such as mass and volume, was given with no further explanation on moisture.

In conclusion, timber production is a complex and articulate process that requires long times and big amount of lands. This combined with the land use change aspect make forestry one of the most complex and difficult sector to run an LCA study on.

Bosner (2012) claims that forest production should be standardized in order to facilitate the inclusion of all possible aspects into an LCA study. Klein et al. (2015) as well propose for a generalized LCA method of the forest production demonstrating how this normalization process are lacking and highly wanted by researchers and people involved in this kind of operations.

Regardless of all the drawbacks and problematic aspects; Klein et al. (2015) who surveyed 20 years of LCA in forestry reported, as showed inFigure 2, that the number of LCA studies increases over time demonstrating an increasing importance of LCAs for forest production. Klein states also that the reason for that is related to the economic importance of biomass especially for energetic purposes and paired with an increasingly public interest to environmental issues. Matching these two aspects, the EU comes along with specific policy targets.

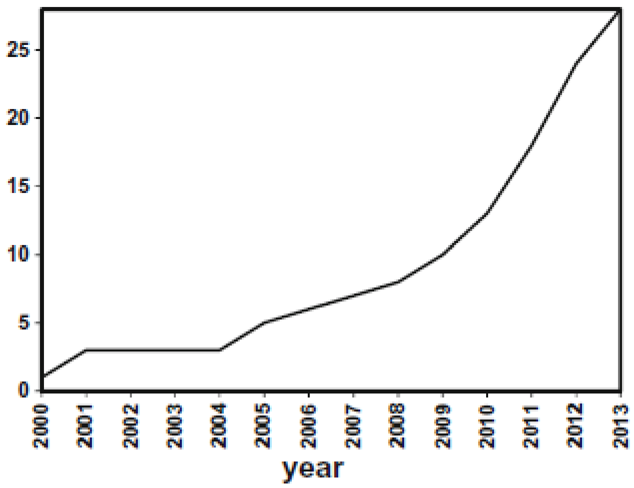

Figure 2: Cumulative studies about LCA in forestry (Klein et al., 2015)

Before the year 2008, in average 5 scientific publications have been produced per year in the field of “LCA and forestry”. After that, the importance of analysing environmental aspects increased, the methods and databases were getting better and as well a boom in bioenergy lead also to a boost of related studies. Nowadays, about 60 publications were produced per year (Figure 3).

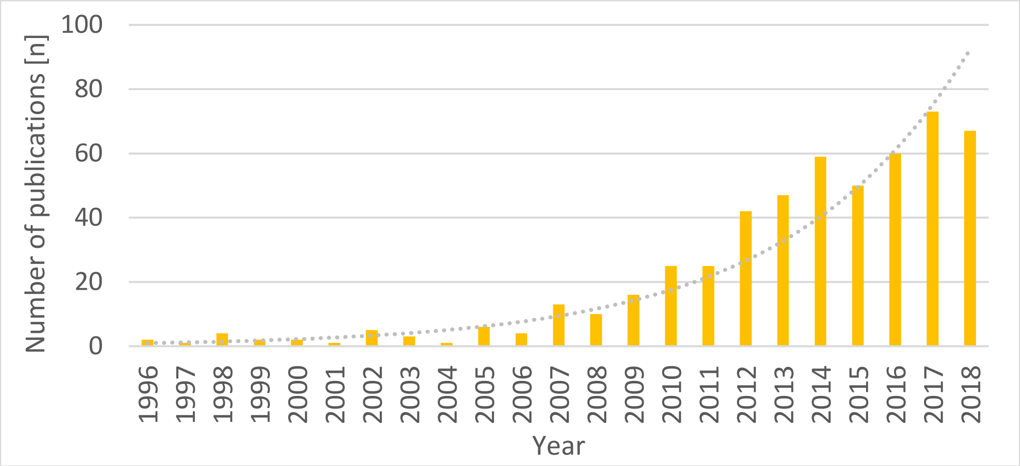

Figure 3: Studies about "LCA and forestry" published per year

3 MATERIAL AND METHODS

3.1 Material gathering

This thesis work can be categorized as “literature review” and for this reason one of the first steps in the making of this thesis has been the gathering of all the possible materials; intended as scientific publications, reports, articles, master and PhD thesis and technical files. The system boundaries of the study were set to be closely related to forestry considering only machines used for plantationsand close to nature systems. Machines that can be potentially used for forestry but were used for other uses, such as agricultural and construction one, were left behind and not included in this study.

The main tools used for the research of the materials were Scopus and Google Scholar. The research strategy was to query for key words related to the research question such as fuel consumption, emission, forestry operation and forest machinery paired with Boolean operators (AND, OR), then looking for other publications from the same author. The first selection to identify useful articles was made searching for more specific key words in the article itself, using the default research tool of the pdf reader. If the publication was relevant for the thesis it was downloaded and named with first author’s name and publishing year (i.e. Manzone, 2013). In case the same author published more than one article the same year the article’s nomenclature was the same as above with a “b” and following letters if the publications were more than two, added after the year (i.e. Manzone, 2013b).

A small share of the publications collected doesn’t comes from Google Scholar nor Scopus. Some of them were directly requested to the author (i.e. Spinelli, 2006) via ResearchGate or via email. Other sources were also personally shared inside the Institute of Forest Engineering of the University of Natural Resources and Life Sciences of Vienna.

At the end of this phase a MS Excel file was created (Appendix A) with the list of all the publications used, divided by forest machine and reporting: (1) type of publication, with dedicated abbreviations (See section 8.3); (2) if the data reported were fuel data, emission data or both and (3) if the article reported any data regarding tree species and/or site conditions.

3.1.1 FORMEC database

This thesis’ work shares part of its objectives with an ongoing project in the University of Padua (Cosola et al., 2016). FORMEC is an international meeting where scientists gather to discuss about forest engineering matters and to start cooperation between different insititutes. Following a FORMEC meeting this project was started by the University of Padova and gathered all the publications and researches about fuel consumption and emissions in forest operations of more than 20 years studying more than 500 harvesting conditions. All of them were recorded in a database in Microsoft Access.

This thesis took a lot from the abovementioned database using its structure as starting point for the creation of this work's one, starting from the structure itself going to the abbreviations going through the productivity's equations. Though the starting point was very similar the goal and scope of the two work are a bit different as the one made under the FORMEC framework. The latter was more focused on the management aspect rather than on the machine level, grouping data for felling and primary transport, chipping and secondary transport.

This works tries to be as similar as possible to the one proposed by Cosola et al. (2016), to make the merging of the two a lot easier and faster to provide a bigger amount of data available.

3.2 Databases

As result of the research work three databases, with similar features, were produced in the making of this thesis work, all of them in MS Excel.

A list of all the publications is the first product of this master work. In this Excel file every publication is reported and additionally which machines are mentioned and if they report fuel and/or emissions data and site specifications and wood specifications.

The second one reported all data with the publication's measure unit divided for the 12 machines listed also in the FORMEC database (section 9.4). The listed machines were, in alphabetical order: cable yarders, chainsaws, chippers, excavators, forwarders, harvesters, harwarders, loaders, skidders, slash bundlers, tractors, trucks. In the same database every machine has his own Excel sheet.

The second database was structured differently for every machine, but every machine had some common variables, in fact all the features were grouped in five main categories:
- machine specifications
- fuel consumption
- emission
- site specification
- wood specification

The first two columns report characteristics of the publications themselves, firstly the code used to get back to values' publication of origin and the type with abbreviations (as shown in section 9.3). For the machine specifications manufacturer, model and power were listed for every machine, then different and machine specific features were listed (i.e. boom outreach, grapple or cable, tyres or tracks…). One last important feature listed in this category is the machine's productivity. Following this category, the consumptions' one, with fuel and lubricant consumption rates. After the consumptions' group the emission's one is placed reporting CO_2 eq. emissions. The last two groups are site specifications, with slope and altitude; and wood specification were tree species and management information are placed.

The last database reports only some selected columns; particularly power, productivity, fuel consumption, emissions and slope, all these preceded by a code for the publication. This selection was made in order to make it easier to upload all the data into RStudio, after eliminating the least complete columns. The code it's equal to the first and second database reporting the publication's author name and the year. The main function of the last one was to report all the data with SI units used in Europe to compare these data. The units were chosen among the most represented ones in the previous database and were respectively kilowatts for machine power, m^3/PMH for productivity, l/PMH for fuel and lubricants consumption and have been considered and subsequently transformed all the equivalent forms such sa; h, SMH, PMH15, E and E15 (description at section 7.5), in the graphs' axis those measure units are reported in l/h for space and digits reasons. (Spinelli, 2006; Spinelli, 2008); emissions in kg/PMH and slope in percentage.

From the beginning some machines' categories were excluded by any kind of preliminary analysis and/or calculation because reported less than 10 values and some others from specific statistical analysis because the lack of data where reported not to be a satisfactory number to produce reliable data.

3.3 Normalization

Another step before the statistical analysis was necessary to make the data comparable and ready to import them in RStudio software. This software is a statistical program used during the statistical analysis phase. It's important to normalize the data to make them comparable. The values captered during the data collection of the publications were different to each other and not under the SI system. This, combined to the fact thatin certain situations it was not possible to convert the value to the SI unit of measure due to lack of data, made the normalization phase the first blocking factor to some publications (England et al., 2003). In certain case, like when different tests were taken with the same conditions, to avoid redundancy of data, it became necessary to average some sample's repetition. Fuel consumption data were averaged if reported for different management techniques, harvesting intensities and with different tree species, but not when the machine used was different and/or the reported productivity different as well. One of the most repeated calculation made in this phase was to extrapolate the fuel consumption in l/PMH from the productivity values (i.e. Johnson et al., 2005).

In details, where the plots or study areas were too big to have a tangible or reported influence on machines' performance, such as countries or area with not specified site characteristics (Berg, 2003; Markoff, 2006; Puttock, 2005). If the harvesting system beckerreported different results for similar or not distinguished sites, the mean value was calculated for each variable.

In some publications reported fuel consumption data was taken from other publications already mentioned in this work as in Becker et al. (2011) and Brinker (2002); or taken from other technical database such as Ecoinvent. Even if the fuel consumption data were not the original result of the research taken into consideration this thesis' work used nonetheless these data to highlight the correlation of average fuel consumption with other parameters such as machine power and/or machine productivity.

A lot of the publications gathered at the beginning couldn't be used due to the lack or unavailability of data. For instance, a lot of publications were left behind because they had problems during the conversion phase because unclear or not convertible, such as the work of Colantoni et al. (2016) where the fuel consumption was reported to be as "less than a tank". Stawicki and Sędłak (2016) reported the fuel consumption in litres over square meters of cutting surface not providing any conversion factor to turn them into l/m^3. Another example of unavailable data is Berg et al. (2012) where all the values referred to the harvesting system and not on the machine.

Assumptions were made and were necessary to normalize the heterogeneity of the second database. Most of the assumptions are based on scientific articles already part of this study or part of the same article themselves. In the following sections all the assumptions and calculation will be listed specifically for those publication where calculations were necessary. The conversion indexes used are different for each machine and taken from the articles and publications studied in this thesis. Some other, general and recurrent conversions factors necessary and used in most of the publications are available in Table 1.

Table 1 - Conversions used and their references (for the abbreviations' meaning see section 7.5)

Conversion	Index	Source
SMH to PMH	1.43	Spinelli, 2006
PMH_{15} to PMH	1	Spinelli, 2008
ft^3 to m^3	0.0283	
gal to l	3.785	
Av. diesel density	0.846 kg/l	Laschi et al., 2016
Av. gasoline density	0.737 kg/l	
Av. daily shift in EU	8h (1 shift per day)	Proto, 2018
Av. daily shift in SAR	9h (2 shifts per day)	Ackerman et al., 2016
hp to kW	0.746	

Yearly machines' use (forwarder)	2068 h/y	Holzleitner, 2010
Yearly machines' use (harvester)	2042 h/y	Holzleitner, 2010
Yearly machines' use (skidder)	1151 h/y	Holzleitner, 2010
Yearly machines' use (cable yarder)	1074 h/y	Holzleitner, 2010
Yearly machines' use (tractor)	2000 h/y	Holzleitner, 2010
Yearly machines' use (excavator)	1525 h/y	Yu et al., 2017
Yearly machines' use (chipper)	2000 h/y	Yu et al., 2017
€/$ yearly exchange	Different for every year	www.ecb.europa.eu
CO_2eq. emissions (trucks)	2.65 kg/l	Holzleitner et al., 2011
CO2 eq. emissions (chippers)	3 kg/l	Van Belle, 2006
CO2 eq. emissions (heavy duty machinery)	3.18 kg/kg	Van Belle, 2006
CO_2 eq. emissions (gasoline)	2.94 kg/l	Handler et al., 2014
Loose m^3 to solid m^3 (chips)	2.63	Kofman, 2010
Tons to m^3	Different according to wood product	www.forestresearch.gov.uk
Over bark to under bark m^3	Different according to wood product	www.forestresearch.gov.uk

Some publications showed some more specific calculations and/or presented some further data inside the article itself. In the following sections all the specific calculations are listed for every relevant machine and publication. As a lot of publication dealt with more than one single machine the following sections may appear repetitive in some part. As shown in the appendix the most represented machines, as for number of values and studies, are intuitively forwarders and harvesters.

Chainsaws are fuelled by a different type of fuel and for this reason have been can't be compared to the rest of the set of machines when comes to fuel consumption and subsequently emissions. Similar logic when it comes to lubricants. Considering these two aspects chainsaws have been excluded from comparative analysis and held singularly.

One final yet very important calculation was made to provide an even more complete database for fuel consumption and CO_2 emissions. These two crucial variables will be reported both over time and quantity. For this reason, the following calculation was made to transform consumption and emission data from l/PMH and kg/PMH to l/m^3 and kg/m^3. The calculation was made, on a Microsoft Excel spreadsheet, only considering the values with both productivity and consumption/emission.

$$FC\left({}^{l}/_{m^3}\right) = \frac{av.FC}{av.PR}$$

Where:

av.FC = the average value of hourly fuel consumption

av.PR = the average value of hourly productivity

3.3.1 Chainsaw

Abbas (2014) reported different productivity data that where averaged with an arithmetic mean.

Aruga et al. (2011) required some additional calculation to express the productivity as for conifers was reported accordingly to the following formula based on the number of stems/PMHa.

$$m^3/_h = \frac{21600V_n\sqrt{N_f}}{219V_n\sqrt{N_f} + 3000}$$

Where:
V_n = average stem volume as m^3/stem
N_f = number of stems harvested per hectare as stems/PMHa

Unfortunately, as these values weren't reported in the publications it wasn't possible to report productivity values for conifers but only for broadleaves that were reported as a simple number with no explanatory formula.

Becker et al. (2011) reported data which are based on Brinker (2002) but not for chainsaws that were measured separately. The values for fuel consumption, by the way, needed to be transformed from $/PMH to l/PMH. The conversion factor for gasoline was reported inside the same publication in the amount of 2.25$/gallon.

Berg (2003) reported two different case studies, Finland and Sweden, each one of those reported also two different harvesting systems (thinning and final cut) and needed to be averaged.

Kofman (2010) showed a lot of repetition for some machines. The values reported in this work are the average values over the repetitions.

Lijewski et al. (2017) described the productivity of a chainsaw as one fourth of a harvester but doesn’t provide any further numerical information.

Engel et al. (2012) showed CO_2 emission data taken from a given model known as *Gemis* (2008 version) and for this reason this work doesn’t report this value but one calculated starting from the fuel consumption data. In this same publication the fuel data to harvest spruce was used only as a backup for the other reported data.

In Enache et al. (2016) the productivity was measured for each different forestry operation, thinning and cut to length and for this reason averaged.

Klein et al. (2016) showed fuel consumption data for different products: stemwood, industrial wood and splitlogs. Because this information was not the focus of the work the values were averaged.

In Koutsianitis and Tsiorias (2017) the productivity was averaged according to the harvesting system.

Pierobon et al. (2015) showed CO_2 emission’s levels as % of the total system’s emission. To increase the accuracy this CO_2 values were not used but calculated from fuel consumption levels.

3.3.2 Harvester

Ackerman et al. (2016) studied the different productivity levels according to the geometry of harvesting scheme held in a eucalyptus plantation. As it’s not one of the objectives of this work the values were averaged.

Athanassiadis (2000) did some research about the different emissions related to different fuel types. This work doesn’t consider the values that describes the performances of RME (rapeseed methyl ester) but only does for diesel fuel, EC1 (Environmental Class) and EC3 averaged. Klvac and Skoupy (2009) did some similar research and as for Athanassiadis the values picked up are the diesel ones.

Both studies of Gonzalez-Garcia (2013, 2014) reported the operating rate (OR) as h/PMHa*yr, the fuel use (FU) as kg/PMHa*yr and in the comment section the biomass yield (BY) reported as m^3/PMHa. The calculation to get the fuel consumption (FC) was as follows:

$$FC = FU/OR$$

Unfortunately, the productivity couldn't be expressed in a measure unit useful for the study.

An extremely similar approach was used by Gasol et al. (2009), and the procedure to calculate the fuel consumption was the same as the one used for Gonzalez-Garcia' research.

Manzone et al. (2009) and Schweier et al. (2015) reported both data about short rotation forestry (SRF). Only Manzone's article could be used in this study as Schweier reported fuel consumption data for an agricultural tractor adapted for SRF.

In 2018 She et al. studied the performances of a harvester and distinguished between operating consumption rates and idling ones. This thesis only considered the first values.

Lijewiski et al. (2017) calculated the fuel consumption starting from the emissions measured from the exhausts directly with portable measuring tools.

3.3.3 Cable yarder

Aruga et al. (2011) reported the machines productivity as a yarding distance formula.

$$m^3/_h = 4.860/(2 * L_y + 243)$$

The yarding distances (L_y) were defined as 100m, 200m and 300m but in the following calculations only the 100m yarding distance was considered. Subsequently the productivity value reported in the database used the lowest yarding distance as variable.

Markewitz (2006) reported data for fuel consumption for the cable yarder itself and the self-propelled carriage. In this thesis the data for the cable yarder was used and didn't consider the values of the self-propelled carriage.

Holzleitner (2010) reported minimum, average and maximum values for both fuel consumption and productivity. For both case the values taken were the average ones.

Laschi (2016) reported data for productivity as stacked m^3/PMH and was transformed into solid m^3/PMH.

3.3.4 Forwarder

Ackerman et al. (2016) studied the different productivity levels according to the geometry of harvesting and extraction held by the operator in a eucalyptus plantation. As it's not one of the objectives of this work the values were averaged.

Athanassiadis (2000) did some research about the different emissions related to different fuel types. This thesis doesn't consider the values that describes the performances of RME (rapeseed methyl ester) but only does for diesel fuel, EC1 and EC3 averaged. The Environmental Class (EC) describes a European classification system for diesel fuel based on their environmental characteristics. Klvac and Skoupy (2009) did some similar researchand as for Athanassiadis the values picked up are the diesel ones.

In Berg (2003) there was no exact difference between farm tractor and small forwarder's fuel consumption values, as written in the publication's material and methods. This thesis assumed the data only for small forwarders.

Brinker (2002) didn't show any productivity value but a percentage of hours on the yearly use. These measures couldn't be used.

Both studies of Gonzalez-Garcia (2013, 2014) reported the operating rate (OR) as h/PMHa*yr, the fuel use (FU) as kg/PMHa*yr and in the comment section the biomass yield (BY) reported as m^3/PMHa. The calculation to get the fuel consumption (FC) was as follows:

$$FC = FU/OR$$

Unfortunately, the productivity couldn't be expressed in a measure unit useful for the study.

An extremely similar approach was used by Gasol et al. (2009), and the procedure to calculate the fuel consumption was the same as the one used for Gonzalez-Garcia' research.

Holzleitner et al. (2010), as reported in previous paragraphs, described their values as minimum, average and maximum but in this study only the average ones are shown.

The productivity in Klein et al. (2016) was based on the different tree species. Like for other similar studies this present work averaged those values because of no interests for this study.

Pandur et al. (2018) reported its productivity in a non-numerical form, this study doesn't take these values.

The reaearch of Rottensteiner (2008) should be noted because it uses a forwarder with a processing head. This study put this machine in the forwarder section rather than putting it in the harwarder's one because the machine's purpose remained the extraction of timber.

Another modified machine used as forwarder appeared in the work of Spinelli (2006) where he reported as forwarder a modified dumper where they removed the bucket and set it as a forwarder.

3.3.5 Skidder

Blouin (2013) studied the performances of a skidder and reported the productivity based on the tree size. This made the data not profitable for the study.

Maesano et al. (2013) showed the productivity as m^3/PMH*worker. This work considered one worker at a time to run a skidder.

Proto et al. (2018) calculated the machine's productivity as a percentage of the total Productive Machine hours (PMH) of the entire system.

Vusic (2013) reported different values for different types of diesel, the values for fuel consumption were averaged.

3.3.6 Tractor

Aruga et al. (2011) researched the productivity and fuel consumption of, between the others, tractors. The research expressed the productivity levels as follow:

$$m^3/_h = \frac{5440}{L_y}$$

L_y = extracting distance in m.

Unfortunately, as the extracting distance was not listed in the paper the productivity couldn't be calculated.

Dias et al. (2007) reported the efficiency in h/m^3 and obviously and quite logically were turned into productivity in m^3/h.

Lovarelli et al. (2018) analysed the performances of tractors and reported both fuel consumption and productivity as measure unit over hectares and not over hours. As there was no further indication to convert the data it was impossible to calculate the values and add them into the dataset.

3.3.7 Excavator

Do Nascimento Santos (2016) did researche on the performances of excavator-based harvester at different revolutions per minute (RPM). The considered values were the one at 1900 rpm, as considered the normal operating rate.

Manzone (2015) studied the productivity of an excavator-based harvester in processing whole trees, from debranching and cross cutting them. This study reports the average of the two samples.

3.3.8 Loader

In the study of Dembure et al. (2019) the loader's productivity was paired with the harvester one making this value unsuitable for both chainsaws and loaders.

Quite a number of studies studied the different performances of the loaders while loading and while sorting. Whenever this happened the study reported an average value.

3.3.9 Chipper

Abbas (2014) made a survey on 31 machines reporting already averaged fuel data and the standard deviation values. In this work only the fuel consumption data was picked.

The fuel values in Laitila and Routa (2015) were calculated based on the annual average fuel cost.

Nati et al. (2014) showed productivity and fuel consumption data for two different samples. Firstly, they studied chippers with dull knifes then as a normal grinder. The values reported in this study are average ones.

Picchio et al. (2012) described the productivity (m^3/PMH) per number of workers. In the chipper case, as the chipper was self-feeding (mounted on a John Deere forwarder), this work considers one worker only.

Roeser (2012) reported different productivity levels for different tree species. As the fuel consumption didn't change and as the timber types were not the focus of the research the values were averaged.

The CO_2 emission values described in Routa et al. (2012) couldn't be used because they were based on management type and not on machine as initially listed first.

Data from Spinelli et al. (2013) is based on the fuel consumption values of his own previous publication (Spinelli, 2008) but it was selected because the productivity values were specific for the study.

3.4 Global Warming Potential

As stated in the introduction, forestry has a major role in climate change and for this same reason it is important to insert this work into the climate change framework, making it available for further research. This kind of calculation is reliable only for the forestry mechanization sector as these measure units aren't totally valid because they cannot be compared to each other. To do this correctly scientists created a bespoke measure unit that represent how greenhouse gases (GHG) affects climate change.

Global Warming Potential (GWP) is the weight that GHGs have on climate change. Different gases retain radiations differently (IPCC, 2013) and for this reason the Intergovernmental Panel on Climate Change created this appointed measure unit. In the following table (Table 2) all the GHGs are listed and their GW potential, that are measured in CO_2 equivalents; grams, kilograms or tons. The values listed as

GWP are conversion factors that need to be multiplied for the quantity of a certain GHG in order to measure their global warming potential.

Table 2 - Kyoto gasses, IPCC 2013

Greenhouse Gas		Global Warming Potential (GWP)
1.	Carbon dioxide (CO_2)	1
2.	Methane (CH_4)	25
3.	Nitrous oxide(N_2O)	298
4.	Hydrofluorocarbons (HFCs)	124 – 14,800
5.	Perfluorocarbons (PFCs)	7,390 – 12,200
6.	Sulfur hexafluoride (SF_6)	22,800
7.	Nitrogen trifluoride (NF_3)[3]	17,200

Finally, the GWP coming out of this master thesis will be simply calculated as follow:

$$CO_2equivalents = FC * CI$$

Where:

CO_2equivalents = Emissions in kg CO_2 equivalent
FC = Fuel consumption as volume or mass unit/PMH
CI = Conversion index kg/l or kg/kg

The main focus of LCI studies is to highlight the input and output flows of systems taken into consideration but after having an overview of all the publications collected the database showed low numbers of CO_2 emissions' data. The abovementioned equation was used to extract emissions data starting from the more present fuel consumption data. The conversion indexes used, different ones for each machine type, are listed in Table 1 and relies on the same literature used to create the databases.

3.5 Data analysis

The first step in the data analysis was to import all the normalized machine data into the statistical software Rstudio (Version 3.6.0). Rstudio is an open source statistic software that is widely used in scientific analysis.

After that all the datasets; named differently according to the harvesting machines, with the exception of the general dataset called `allmachines` were summarized and showed as scatterplot to identify possible outliers, using firstly the function `plot(fuel$chainsaw)`, reporting the different variables of all machines.

3.5.1 Eliminating outliers

The outliers were analysed jointly with the supervisor of this thesis work: Martin Kuehmaier, accordingly to the usual way to proceed at the Institute of Forest Engineering.

The following table shows the thresholds set for each machine and each parameter. The square brackets tell if the limit set is upper or lower. If no values are shown, no outliers were required.

Table 3 - Outliers thresholds

Machine	Power (kW)	Productivity (m^3/PMH)	Fuel (l/PMH)	Emissions in CO_2 equ (kg/PMH)
Cable Yarder		,12.5]	,20]	,50]
Chainsaw		,14]	,5]	,15]
Chipper	,700]			,250]
Excavator		,22.5]	[7.5,	[20,
Forwarder		,200]	,50]	,120]
Harvester	[50,260]	,70]	,80]	,200]
Loader		[30,	,40]	,100]
Skidder		,200]	,60]	,150]
Tractor	[50,	,25]	,27.5]	,65]

One second round of scatterplots was run to cross check the validity of the data. No further thresholds were necessary. Once the datasets were given as without the outliers the successive step was about data quality.

3.5.2 Data quality

Before performing any statistical analysis it's important to check and eventually improve the data quality. For this reason, the following step was to identify the presence and the incidence of missing values (NAs) in every machine category's database. For this a function was used taken from a specific Rstudio's package called Multivariate Imputations by Chained Equations (MICE). The *mice* package implements methods to deal with missing data creating multiple imputations (replacement values) for multivariate missing data.

Between the others, in the abovementioned package, the function, called `md.pattern` shows a table with the missing values for each variable to help identify the share of missing values. This function is useful for investigating any structure of missing observations in the data. Also, the missing pattern could suggest which variables could potentially be useful for imputation of missing entries. And to have any statistical validity the missing values shouldn't exceed 5%.

As the missing values were a big concern for the validity of this work it appears that different strategies were adopted along the whole thesis to deal with them, from simple commands to more complex approaches. There are some generic functions which are useful for dealing with NAs in e.g., data frames. `na.fail` returns the object if it does not contain any missing values, and signals an error otherwise. `na.omit` returns the object with incomplete cases removed. `na.pass` returns the object unchanged. For this specific thesis' work, specifically for the descriptive statistical analysis, it was enough to get rid of the NA values with the `na.omit` command, removing cases with NA values.

The already mentioned and used *mice* package was also important as imported the predictive mean matching (PMM) approach that make a random draw from the "posterior predictive distribution" of a certain set of coefficients, producing a new set of coefficients. Predictive Mean Matching (PMM) is a semi-parametric imputation approach. It is similar to the regression method except that for each missing value, it fills in a value randomly from among the observed donor values from an observation whose regression-predicted values are closest to the regression-predicted value for the missing value from the simulated regression model (UCLA). The PMM method ensures that imputed values are plausible; it might be more appropriate than the regression method (which assumes a joint multivariate normal distribution) if the normality assumption is violated.

It's run as followed taking into consideration the length of the dataset, as stated by the CRAN-project, one of this work's sources, a network where all the Rstudio's codes are listed to help people out.

```
pMiss <- function(x){sum(is.na(x))/length(x)*100}
apply(chainsaw,2,pMiss)
apply(chainsaw,1,pMiss)

csd <- mice(chainsaw,m=5,maxit=50,meth='pmm',seed=500)
summary(csd)
cs1 <- complete(csd,1)
```

After that a new database was complete reporting no NA values making further analysis possible. In this thesis' case the linear models' analysis have been done using the new databases resulting from this process.

3.5.3 Descriptive statistics

The majority of the descriptive statistics of the datasets was done will the help of the summary command on Rstudio. This command returns a table reporting the main information of a given dataset divided by variable, for each of which are described: first and third quartile; mean, minimum and average value and the number of missing values (NAs). The following lines describes exactly the procedure undertaken to create the summaries that are listed in the results section. The summaries have been saved externally, in another folder, to preserve the data (second calculation line).

```
summarycs<-summary(chainsaw)
write.table(summarycs,"C:/Users/aargnani/Desktop/THESIS/excelfiles/Machi
ne/summarycs.txt", sep="\t")
```

Unfortunately, the summary command wasn't complete enough to be satisfactory on his own. Two more major information were added in order to create a more complete descriptive statistic.

Standard deviation and standard error were calculated as follow. It's important to note that only for the variables power and productivity two new datasets were drawn to not consider the NA values with the `na.omit` command, power and productivity

```
cspo<- na.omit(chainsaw$power)
cspr<- na.omit(chainsaw$productivity)

sd(cspo)
sd(cspr)
sd(cs1$fuel)
sd(cs1$CO2)
```

Successively, the standard error was calculated accordingly to the following mathematical formula:

$$SE = \frac{SD}{\sqrt{n}}$$

Where:

SD = standard deviation
n = number of observed samples

The abovementioned formula was entered manually in Rstudio script and repeated for each variable and machine category.

As all the data is shown in hourly units. To provide a more complete work, fuel consumption and CO_2 equ emissions are also reported as volumetric unit (l/m^3 and kg/m^3 of timber). Unfortunately, the data was not complete enough to provide all the descriptive statistics with all the other variables. For this reason, the calculation was only made based on the mean values of productivity and the fuel consumption and CO_2 emissions respectively using the following formulas:

$$FC_V = \frac{FC_h}{P}$$

$$E_V = \frac{E_h}{P}$$

Where:

FC_V = volumetric fuel consumption in l/m³
FC_h = hourly fuel consumption in l/PMH
P = productivity in m³/PMH
E_V = volumetric emissions in kg/m³
E_h = hourly emissions in kg/PMH

Another important aspect of the descriptive statistic were regression lines. Regression lines give an idea of how two variables are related, and these lines were drawn as follows using the specific *ggplot2* package. The *ggplot2* is based on the grammar of graphics and is widely used.

The first step in the drawing the linear regression was to create a data frame specific for each correlation wich was useful for this work's analysis. The following two lines represent how, with a simple command, two databases were created reporting only the interesting variables separately. As explained in the previous paragraphs, the CO_2 emissions were left behind because calculated mostly from the fuel consumption data and not significantly different from them.

```
df.chainsaw <- data.frame(chainsaw$power, chainsaw$fuel)
df.chainsaw1 <- data.frame(chainsaw$productivity, chainsaw$fuel)
```

The ggplot function comes in helping the drawing phase as it visualizes the scatterplot and its regression line in three statements. The first line here after representing the one command that indicate the source and the components. The second line specify the points in the plot and the last one represent the geometric function that adds the regression line with the specific method, linear model in this thesis' case. The three lines merged together with the plus sign create the graph of interest shown in the results section.

```
ggplot(df.chainsaw, aes(y=chainsaw.power, x=chainsaw.fuel))+
geom_point()+
geom_smooth(method = lm)
```

The *aes* code has a purely aesthetic function, giving name to the axes and adding a grey background to the plot.

Further descriptive statistic was done on all the diesel-driven machines to compare them in one single graph. The very first step was to create a dataset that fitted the Rstudio commands, all the machines were put in one dataset and only few, selected parameters were added. After that the machine category was added in a different column. The parameters under investigation were power over fuel consumption and specific fuel consumption per cubic meter for single machine. The following lines shows how this has been done.

The first line shows the code that eliminated the chainsaws from the dataset as not diesel fuelled and completely different in term of power and productivity.

```
df.diesel <-  subset(df.all.unique, type != "chainsaw")
aggregate(fuel ~ type, data = df.diesel, FUN = basic.stat.ft)
aggregate(power ~ type, data = df.diesel, FUN = basic.stat.ft)
```

After that the functions were listed for the two models analysed with the aggregate function. In the end the plot was designed following the linear model function.

```
  ggplot(df.diesel, aes(x=power, y=fuel, color=type)) +
   geom_point() +
   geom_smooth(method = "lm")
 ggplot(df.diesel, aes(x=power, y=spec_fuel, color=type)) +
   geom_point() +
   ylab("specific fuel consumption l/mÂ³")
```

3.5.4 Linear models

A comprehensive R package for environmental statistics called Environmental Statistics (abbr. EnvStats) provides a set of powerful functions for graphical and statistical analyses of environmental data. A second package was necessary to develop linear models and it was the so-called *e1071.* Once all the packages have been downloaded and opened the series of codes for the creation of the linear model was written. In this paragraph the chainsaw's productivity and power values have been taken as an example. As for the rest of the database the abbreviations and names of the databases are made to remind easily the type of machine that are studied (i.e cs stands for a complet database for chainsaws).

The skewness of the histograms is a function that gives the position of the density as histograms as a measure of the asymmetry of the probability distribution of a real-valued random variable about its mean. If the density distribution is symmetric the skewness equals zero; when it's shifted on the left the skewness is negative and inversely is positive when shifted on the right, that means that the tail of this distribution lays on the right.

Before running a linear model it's important to identify if the sample is normally distributed or not. The skewness identifies, whether it's close to zero (and less than 1) and therefore a normal distribution. After having identified the normality of the values in the given distribution the density of the data is measured as follow:

```
plot(density(cs1$power), main="Density Plot: power", ylab="Frequency", su
b=paste("Skewness:", round(e1071::skewness(cs1$power), 2)))
plot(density(cs1$productivity), main="Density Plot: productivity", ylab="
Frequency", sub=paste("Skewness:", round(e1071::skewness(cs1$productivity
), 2)))
```

The density is visually represented with these simple codes:

```
polygon(density(cs1$power), col="blue")
polygon(density(cs1$productivity), col="blue")
```

The correlation values are crucial to identify if there's any correlation between the appointed variables and, specifically no linear models could be run if the correlation was lower than ±0.3. For this reason, in this phase a lot of potential linear models had to be excluded. The correlation values, due to their high importance are shown in the results section.

```
cor(cs1$power, cs1$fuel)
cor(cs1$power, cs1$productivity)
cor(cs1$productivity, cs1$fuel)
```

To identify the model coefficients, meaning those values that were generated by the summary function, it's important to capture model summary as an object in order to use it as a database itself.

```
modcs1<-lm(power~fuel, cs1)
summary(modcs1)
```

The coefficients tables show intercept and slope of the regression line values and making it as model coefficients, meaning that the framework of the model was set stable and to get beta estimate for the required variable.

Once the linear equation is identified the equation for CO_2 emissions for each machine category can be easily calculated simply multiplying the equation by the conversion factor.

3.5.5 Fuel trend

One final analysis made on the dataset was to look for any trend in fuel consumption over time. The necessary packages ggplot2 and ggfortify were downloaded to run all the ggplot features and action. The protocol to highlight a trend in fuel consumption over time in Rstudio, as listed below, requires a method to follow. For this reason, a first linear model was run and set as dataset with a code reporting the acronym of the machine, "ch" for chipper in this very case. Then the datasets have been plotted to show the trend over time using a simple ggplot function setting, specifying the axes and the method that the lined should have followed, the linear model.

```
ch_tmult<- lm(fuel~year+power, data = ch_time)
ggplot(ch_tmult, aes(x=year, y=fuel)) +
   ylab("fuel") +
   xlab("year/power") +
   geom_point() +
   geom_smoothv(method="lm")
```

4 RESULTS

4.1 General results

A total number of 170 studies was analysed at the end, most of them were researches and scientific articles and only a few were books and/or conference papers. Out of these 170 studies a total of more than 700 values resulted and have been analized. In appendix 8.4 the literature database shows exactly the number of studies that reported fuel data, emission data or both (Figure 4). As shown in figure number 4 fuel consumption-only studies are the most represented in this study literature. Only emissions are not really present in this list as emissions' studies often couldn't be used as part of generic LCA studies and/or studies not focusing or even reporting machine's data.

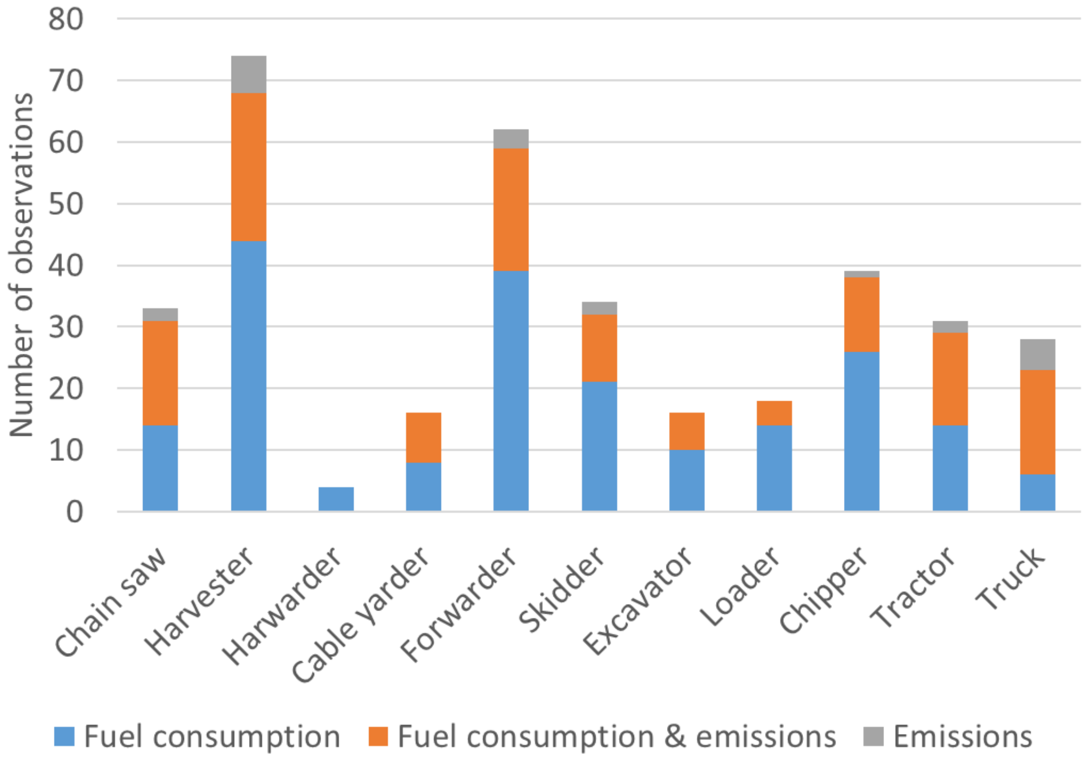

Figure 4 – Number of observations covering fuel consumption and emission data

The results coming from the general analysis on all the machines together highlights that the highest power outputs are displayed by chippers, matched with a high variability, similar to the cable yarder's one. On the opposite tractors shows the lowest power output (Figure 5).

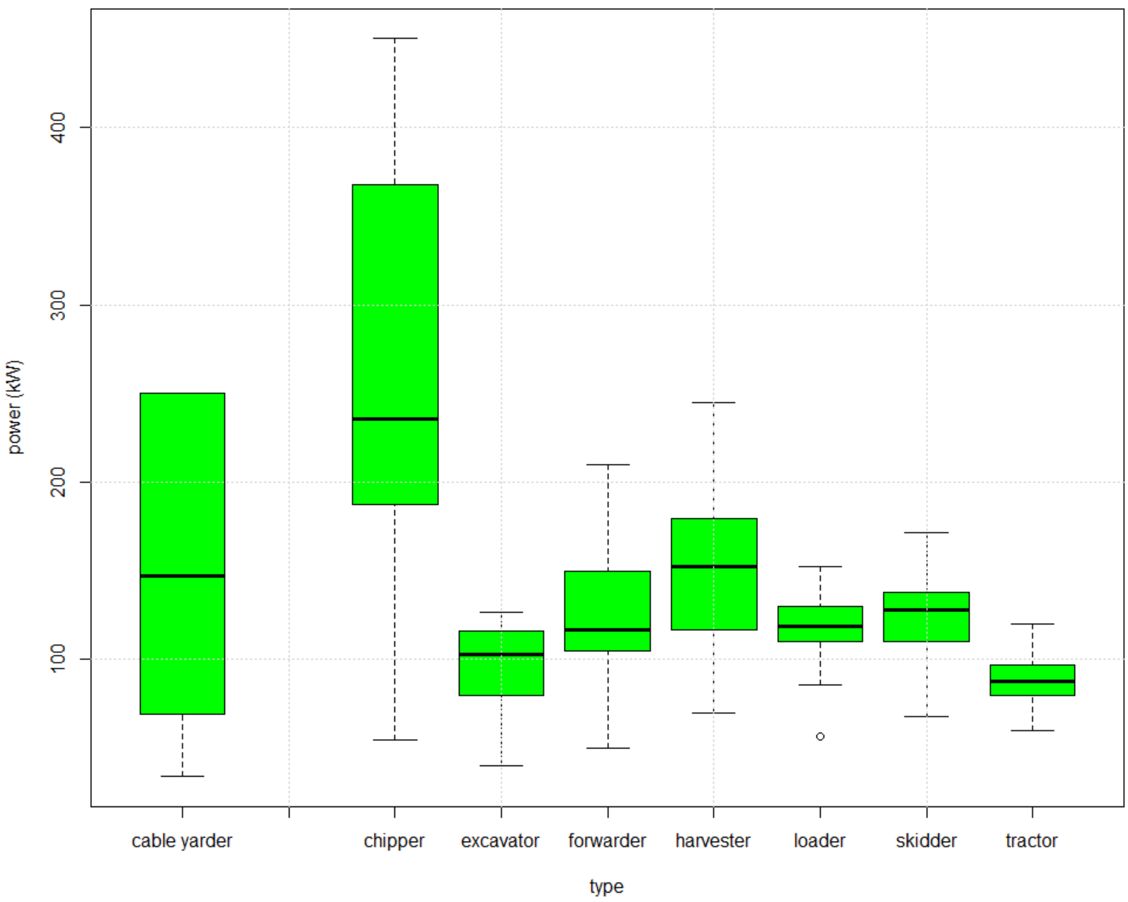

Figure 5 - Diesel driven machines' power in kW

As regard the productivity, as expected the lowest levels are given by cable yarders and tractors and highest by the loaders and the chippers. Chippers show, even in this case the highest variability (Figure 6).

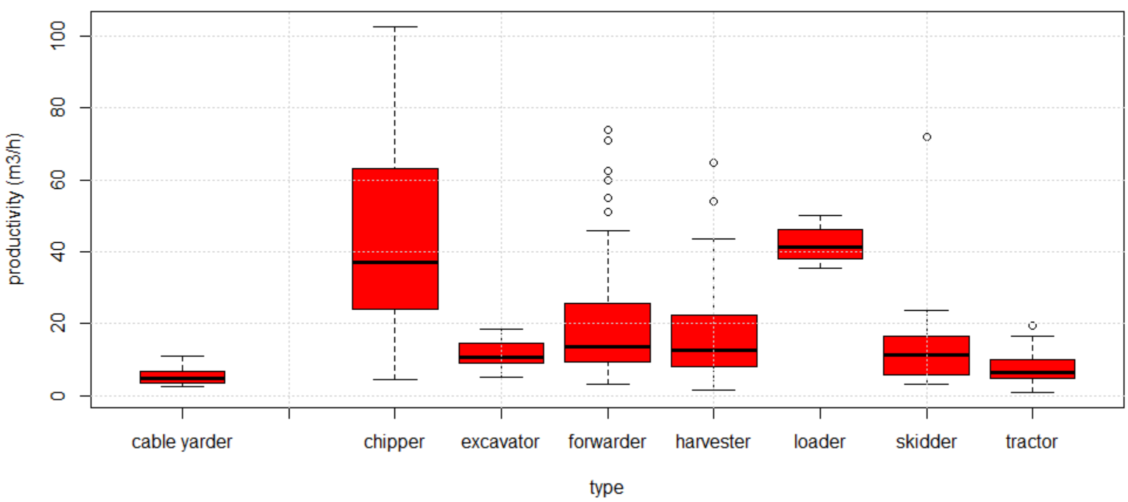

Figure 6 - Diesel driven machines' productivity in m^3/PMH

Fuel consumption's levels appears to be quite homogeneous regardless of the machines. As expected, the highest levels are shown by the big chipper trucks and again the highest data variability lies on chippers. Important to notice that chippers and forwarder have values far from the mean, even after removing the outliers (Figure 7).

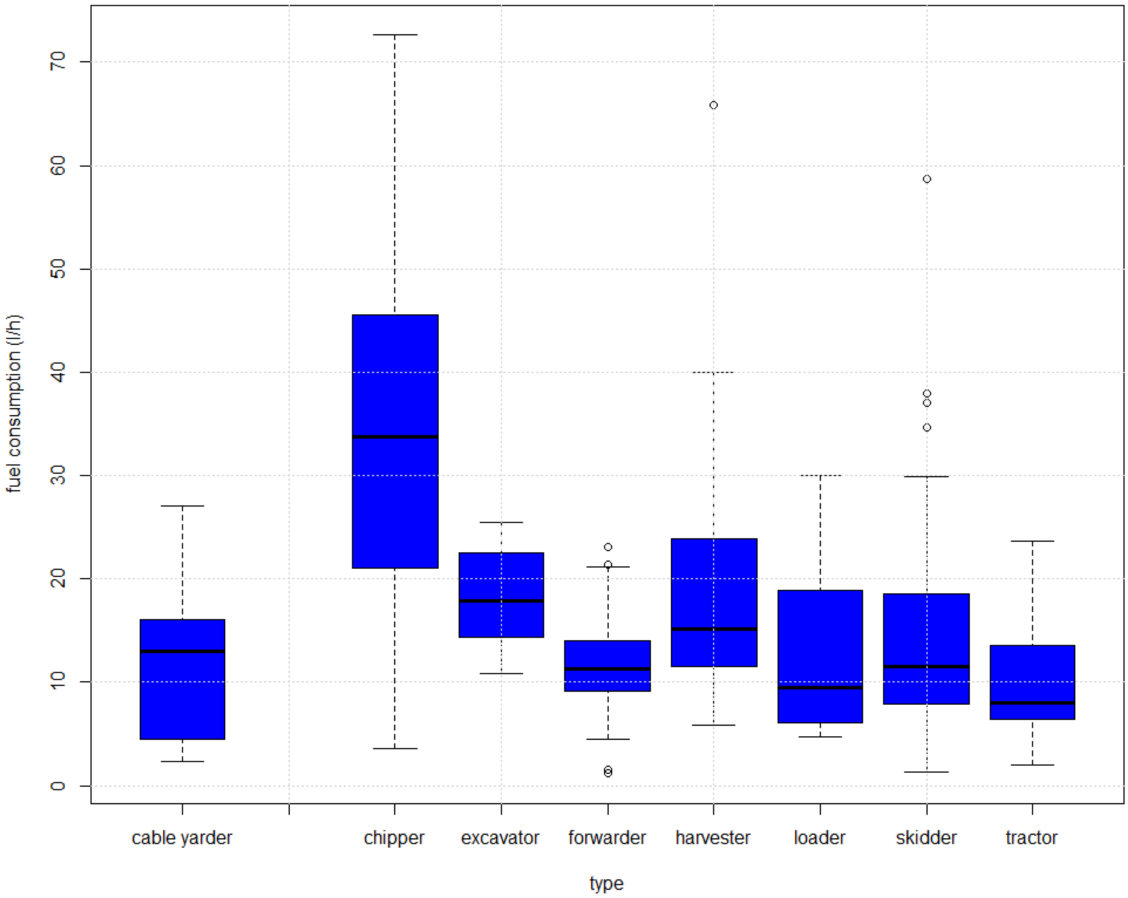

Figure 7 - Diesel driven machine's fuel consumption in l/PMH

As calculated starting from fuel consumption, the emissions values in CO_2 equivalent are extremely similar to the fuel consumption levels showing a high variability in chippers and the lowest levels in tractors (Figure 8).

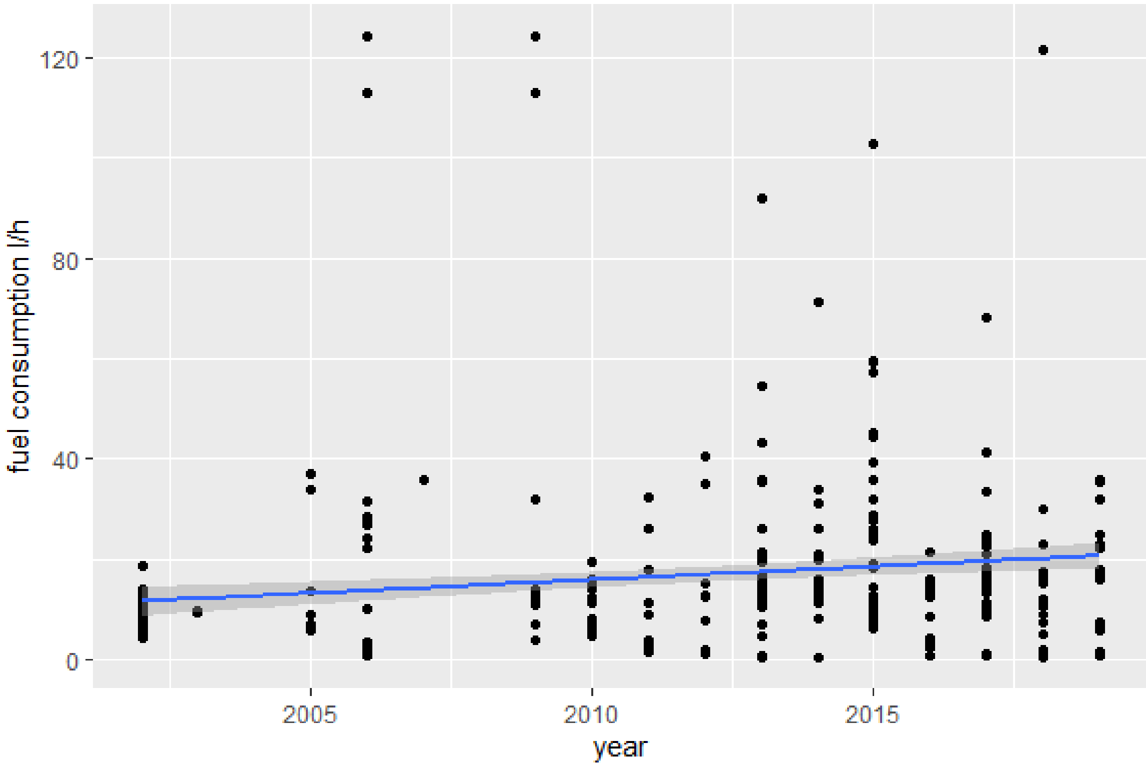

Figure 8 - Diesel driven machines' trend over time (year weighted by machine's power).

In Figure 9 all the diesel fuelled machines are compared as regards power and fuel consumption. The most fuel intensive machine resulted to be the chipper as clearly highlighted by the brownish line. Chippers showed also an extremely high variability. On the other hand, all the other machines show similar values.

In Figure 1010 the same values are reported for specific fuel consumption over cubic meters. The chippers showed a lower fuel consumption value for unit of wood processed.

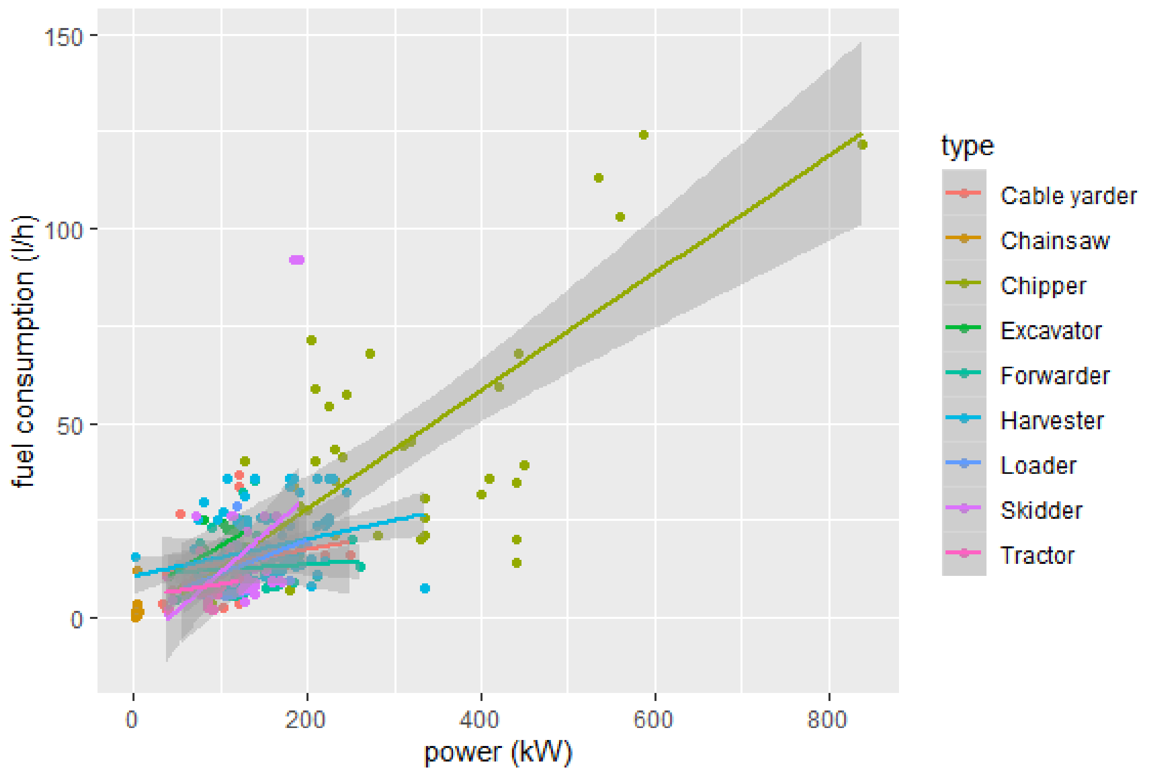

Figure 9 - Diesel driven machine's power and fuel regression

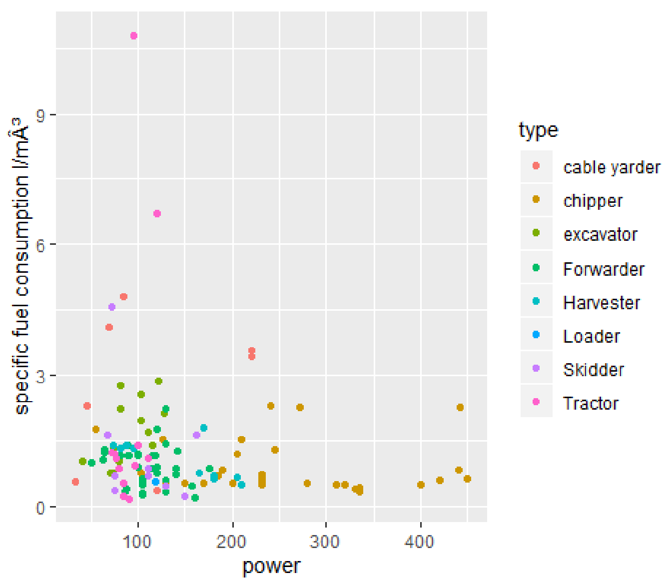

Figure 10 - Diesel driven machine's specific consumption per cubic meter over power

4.2 Specific results

In the following sub sections, the results are shown, reporting all the machines' specifications in alphabetical order. For each machine in the descriptive table the reported characteristic for each variable are the quartiles; first and third, minimum and maximum value, mean and median, NA values, standard deviation and standard error.

4.2.1 Chainsaw

55 sample have been recorded for the chainsaws. In table number 4 the most important values are shown for each variable. Important to notice are is the high level of NA values in the productivity sector, more than a half of the studies didn't report the productivity of chainsaws. The mean power for chainsaws was between 3 and 4 kW being able to produce 6.34 m^3 of timber every hour. The fuel consumption of these machines was reported to be 1.4 l/PMH average.

Table 4 - Chainsaw's summary

	Power (kW)	Productivity (m^3/PMH)	Fuel consumption (l/PMH)	Fuel consumption (l/m^3)	CO_2 equ (kg/PMH)	CO_2 equ (kg/m^3)
Minimum value	2.000	2.030	0.3500		0.805	
1st quartile	2.800	4.173	0.7875		1.811	
Median value	3.500	5.775	1.010		2.323	
Mean value	3.789	6.343	1.382	0.37	3.179	0.86
3rd quartile	4.500	8.750	1.7525		4.031	
Max value	6.400	11.880	4.160		9.568	
NA's value	17/55 (31%)	38 /55 (69%)	/55		/55	
Standard deviation	1.039974	2.903987	0.918562		2.112693	

The regression lines (Figure 11 and Figure 12) of the chainsaws reported a positive correlation for both power and fuel consumption and productivity and fuel as confirmed in **Errore. L'origine riferimento non è stata trovata.**.

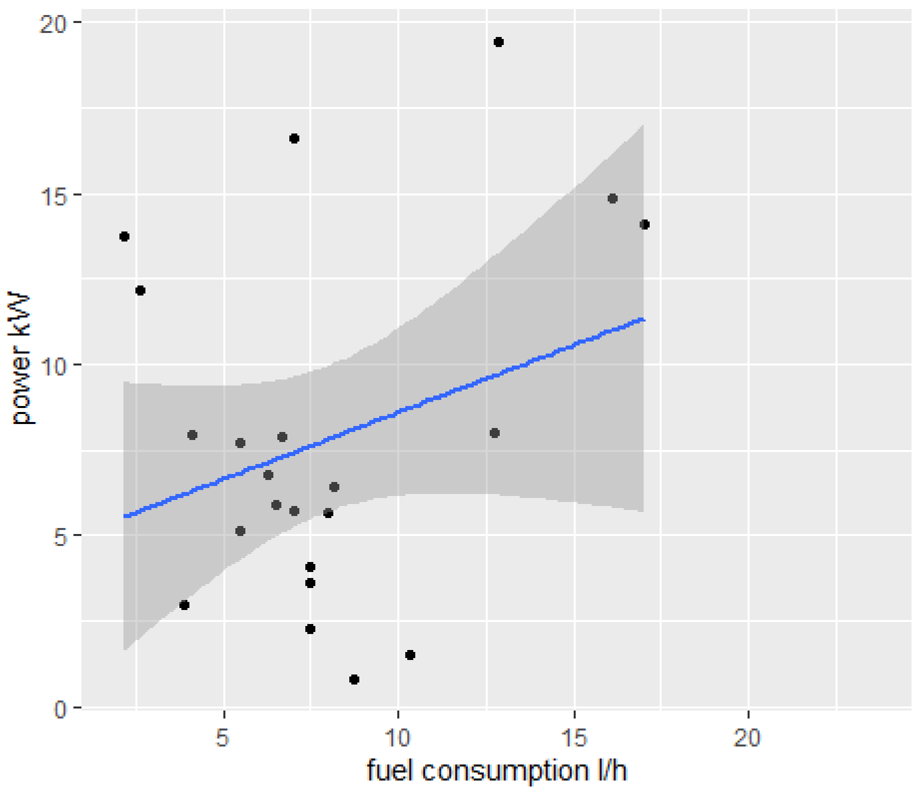

Figure 11 - Regression line of chainsaw's power and fuel

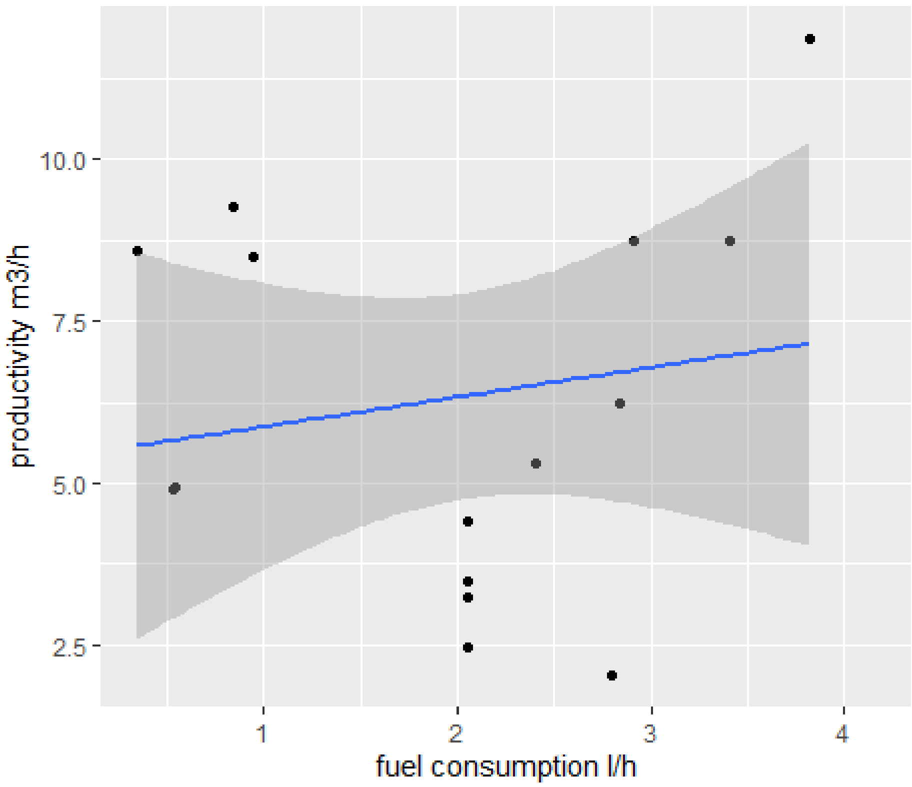

Figure 12 - Regression line of chainsaw's productivity and fuel consumption

Table 5 - Chainsaw's correlation values

Correlations	Fuel	Power
Power	0.3006693	/
Productivity	0.2800877	-0.1766487

The following equation represents the model that describes the fuel consumption considering both productivity and power output of the machines.

$$FC = -0.6329246 + 0.1172562 * productivity + 0.3316388 power$$

Where:

FC = fuel consumption in l/PMH

Productivity = harvesting productivity in m^3/PMH

Power = machine power in kW

In figure number 13 the fuel consumption’s trend is represented with a scatterplot. The results show a little decrease over time.

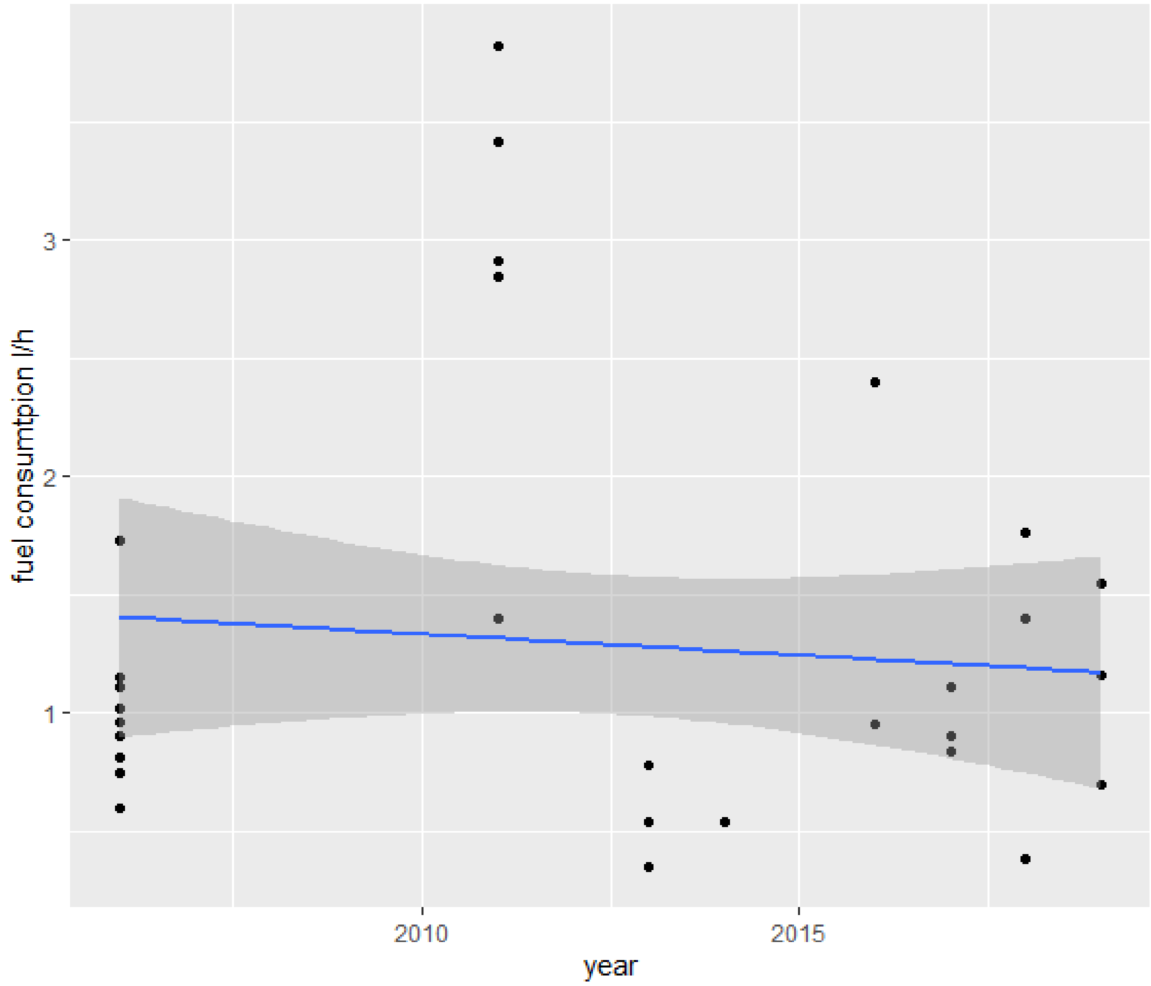

Figure 13 **- Chainsaw fuel consumption over time (year weighted by machine's power)**

4.2.2 Harvester

Harvester are the most studied machine with 208 values in total. This study registered an average power values of 148.5 kW able to process 12.7 m^3 of timber consuming 15.25 litres in one hour. The NA values were 36% of the total for the power and a good 77% of the total for the productivity.

Table 6 - Harvester's correlation values

	Power (kW)	**Productivity (m^3/PMH)**	**Fuel consumption (l/PMH)**	**Fuel consumption (l/m^3)**	**CO_2 equ (kg/PMH)**	**CO_2 equ (kg/m^3)**
Minimum	70.0	1.60	5.90		15.76	
1st quartile	117.8	8.05	11.53		30.80	
Median	152.1	12.70	15.25		40.74	
Mean	148.5	17.32	18.07	1.37	48.27	3.66

3rd quartile	179.2	22.45	23.90		63.84	
Maximum	245.0	64.90	65.86		175.93	
NA's	75/208 (36%)	160/208 (77%)	/208		/208	
Standard deviation	44.67345	13.67944	9.439713		25.21536	

Regressions were studied and reported a steady and positive correlation between fuel and productivity and fuel and power. These are also explained by the values reported in table number 7.

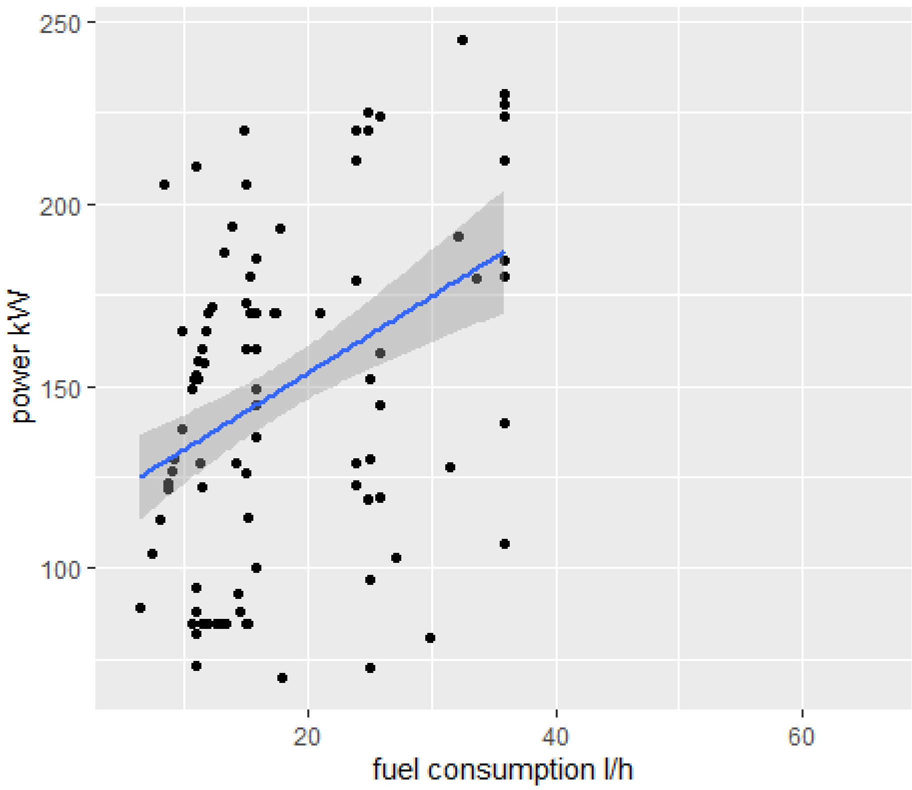

Figure 14 - Regression line of harvester's power and fuel

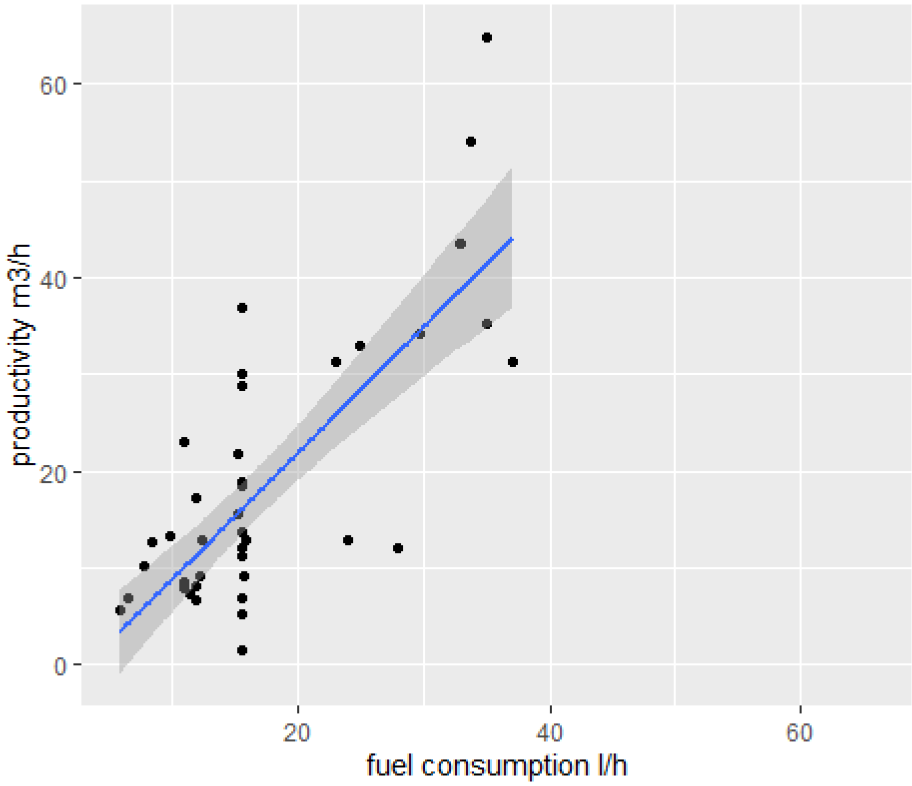

Figure 15 - Regression line of harvester's productivity and fuel

Table 7 - Harvester correlation's values

Correlations	**Fuel**	**Power**
Power	0.3957258	
Productivity	0.7156668	0.5080321

The following equations shows how the fuel consumption of the harvesters is explained by their power and their productivity. Instead in figure 16 fuel consumption over time is shown.

$$FC = 7.9527905 16 + 0.448136008 * productivity + 0.009110366 power$$

Where:

FC = fuel consumption in l/PMH

Productivity = harvesting productivity in m³/PMH

Power = machine power in kW

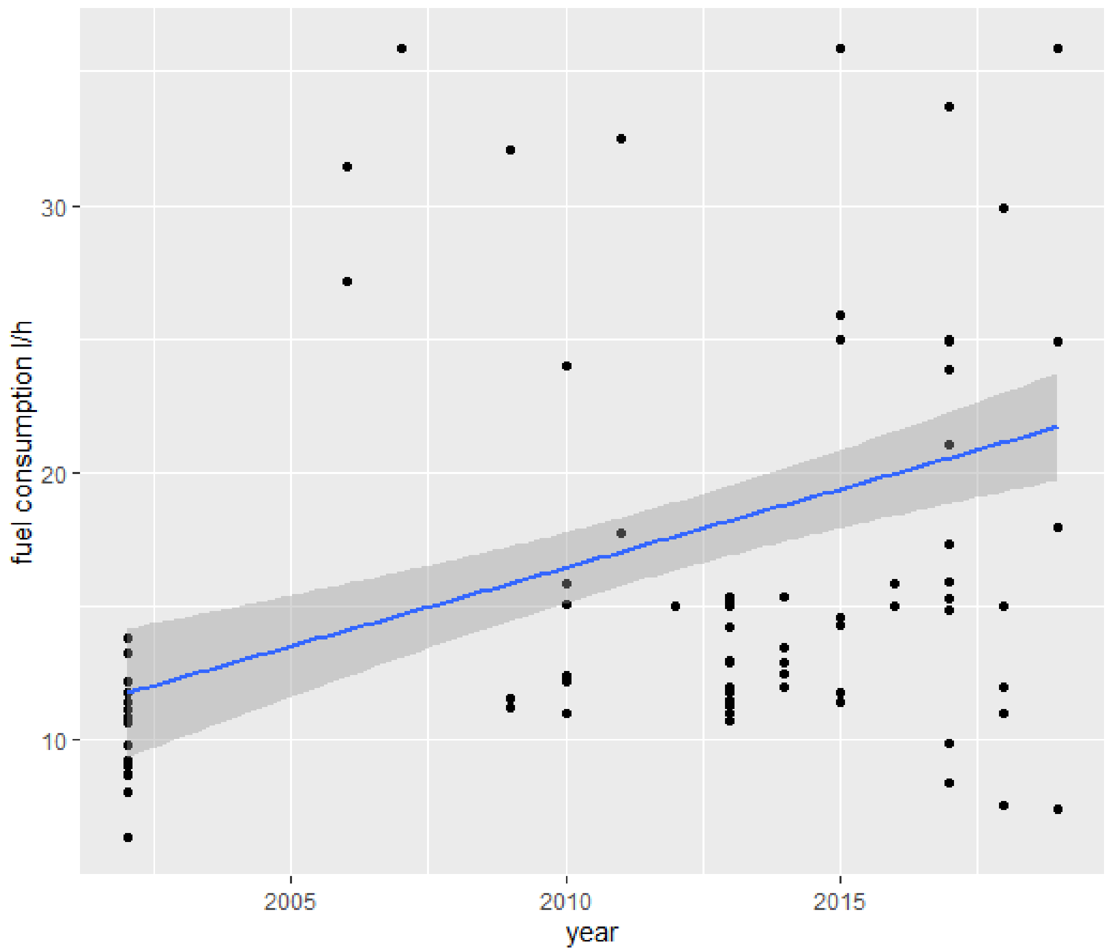

Figure 16 - Harvester's fuel consumption over time (year weighted by machine's power)

4.2.3 Cable yarder

A total of 28 values were registered for cable yarders. In **Errore. L'origine riferimento non è stata trovata.**8 the major characteristics are summarized. The data shows an average machine power of 158.5 kW that can produce and average 5.6 m^3 of timber hourly. Given these values the fuel consumption of these machines appears to be 10.15 l/PMH. The NA values are 35% and 43% for power and productivity respectively.

Table 8 - Cable Yarder's summary

	Power (kW)	**Productivity (m^3/PMH)**	**Fuel consumption (l/PMH)**	**Fuel consumption (l/m^3)**	**CO_2 equ (kg/PMH)**	**CO_2 equ (kg/m^3)**
Minimum	34.0	2.430	2.300		6.217	
1st quartile	84.0	3.585	4.455		12.042	

Median	175.0	4.660	13.000		35.139	
Mean	158.5	5.608	10.151	2.12	27.438	5.61
3rd quartile	250.0	6.740	16.000		43.248	
Maximum	250.0	10.970	16.000		43.248	
NA's	10/28 (35%)	12/28 (43%)	/28		/28	
Standard deviation	88.21555	2.711326	5.493397		14.84865	

The regression line matched with its correlation values (**Errore. L'origine riferimento non è stata trovata.**) showing a positive correlation between machines power and fuel consumption (Figure 17) but oppositely a negative correlation between productivity and fuel consumption is registered (Figure 18).

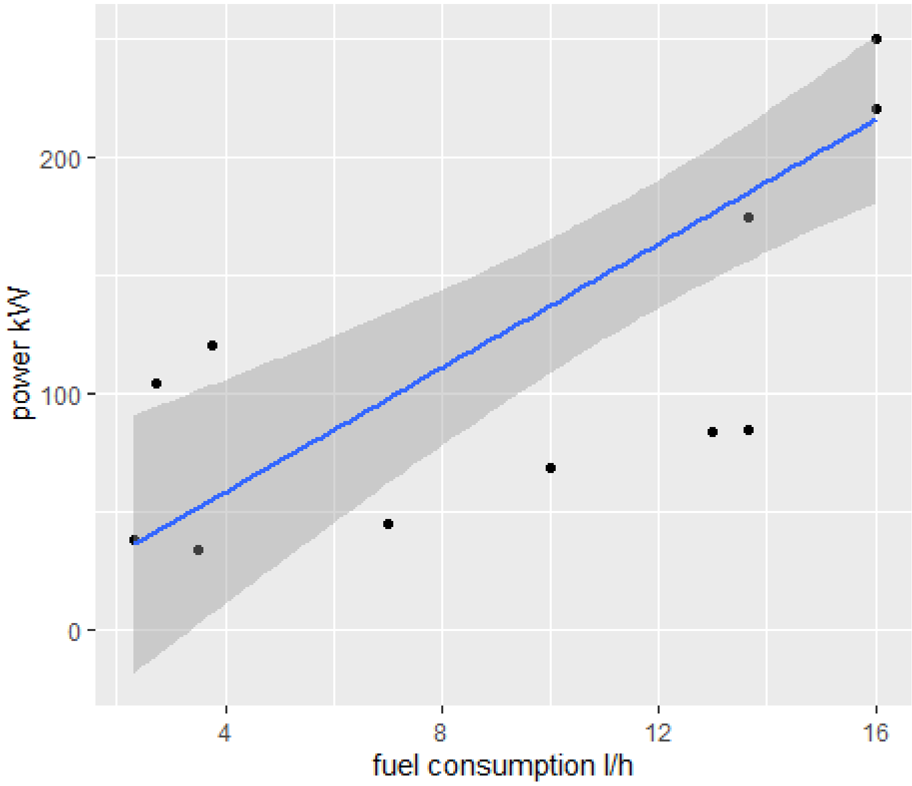

Figure 17 - Regression line of cable yarder's power and fuel

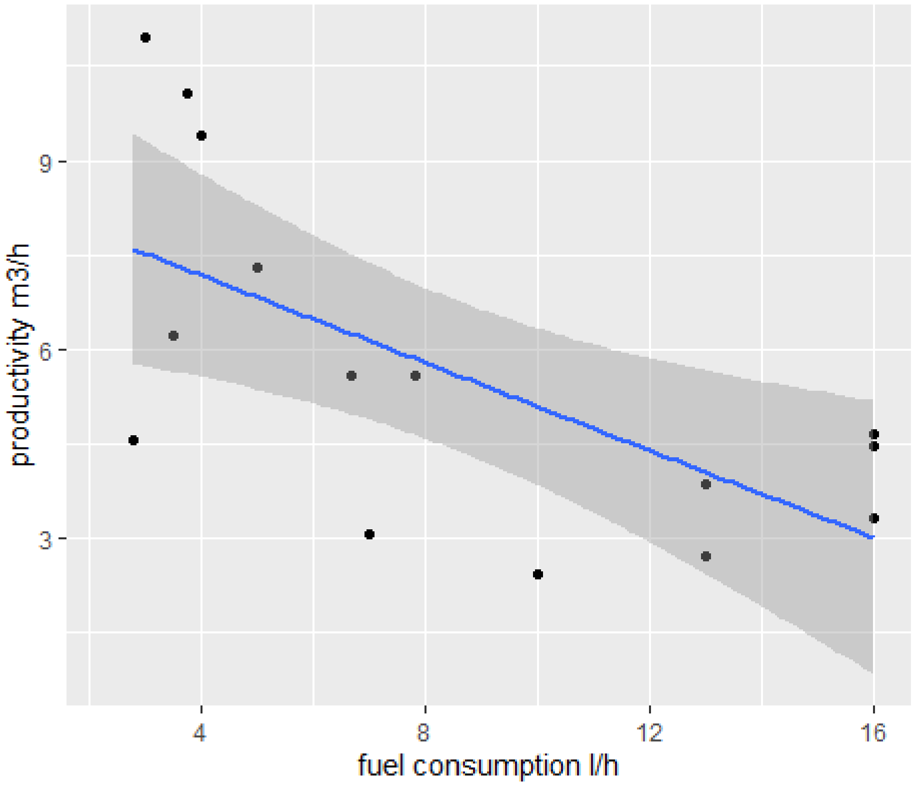

Figure 18 - Regression line of cable yarder’s productivity and fuel

Table 9 - Cable Yarder's correlation table

Correlations	**Fuel**	**Power**
Power	0.7028146	/
Productivity	-0.5455658	-0.06537666

Cable yarders, showed in Figure 19, a slightly decreasing trend in fuel consumption over time.

Analysing the fuel consumption trends over time cable yarders registered a decrease in consumption considering the ratio with machine’s power.

Figure 19 - Cable yarders fuel consumption over time (year weighted by machine's power)

In the following line the fuel consumption model derived from the dataset is written. The productivity highlights a negative trend as expected and as shown in the correlation table (**Errore. L'origine riferimento non è stata trovata.**9).

$$FC = 10.7 - 1.30productivity + 0.05power$$

Where:

FC = fuel consumption in l/PMH

Productivity = harvesting productivity in m^3/PMH

Power = machine power in kW

4.2.4 Forwarder

A total of 128 forwarder's data were registered in this thesis work, being the second most studied machine in the forestry sector. The average power of 127.5 kW is able to extract an average of 26.1 m^3 of timber hourly consuming 12.4 litres of fuel hourly again. The NA values showed a close to 50% percentage for productivity and only a 32% for power.

Table 10 - Forwarder's summary

	Power (kW)	**Productivity (m^3/PMH)**	**Fuel consumption (l/PMH)**	**Fuel consumption (l/m^3)**	**CO_2 equ (kg/PMH)**	**CO_2 equ (kg/m^3)**
Minimum	50.0	3.200	1.15		3.072	
1st quartile	105.0	9.405	9.29		24.815	
Median	118.9	14.650	11.41		30.481	
Mean	127.5	26.075	12.44	0.734	33.232	1.96
3rd quartile	150.0	30.500	14.20		37.931	
Maximum	260.0	168.00	38.69		103.349	
NA's	41/128 (32%)	63/128 (49%)	/128		/128	
Standard deviation	39.87995	28.46456	5.864		15.66392	

The correlation studied was positive for both fuel and power and fuel and productivity as confirmed, visually in figures 20 and 21, and precisely in table 11.

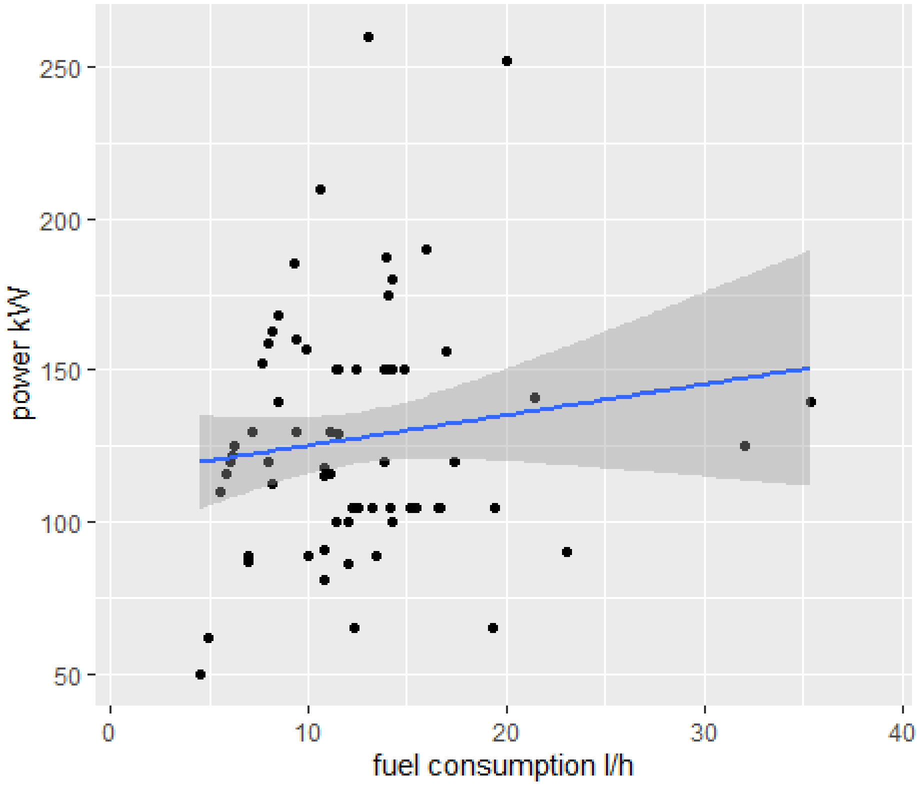

Figure 20 - Regression line of forwarder's power and fuel

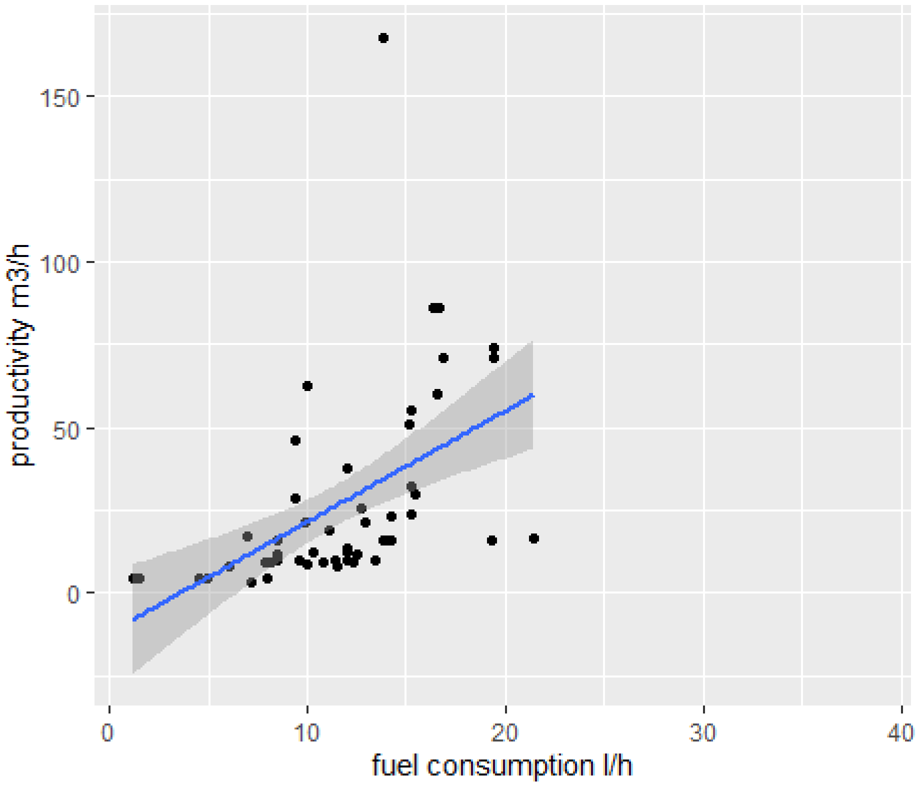

Figure 21 - Regression line of forwarder's productivity and fuel

Table 11 - Forwarder's correlation values

Correlations	Fuel	Power
Power	-0.02327259	
Productivity	0.6129331	0.001306673

The model representing the fuel consumption of forwarders is represented as follow.

$$FC = 9.239729302 + 0.133377192 * productivity - 0.003445973 power$$

Where:

FC = fuel consumption in l/PMH
Productivity = harvesting productivity in m³/PMH
Power = machine power in kW

In figure number 22 the fuel consumption trend over time is represented showing a small increase over time.

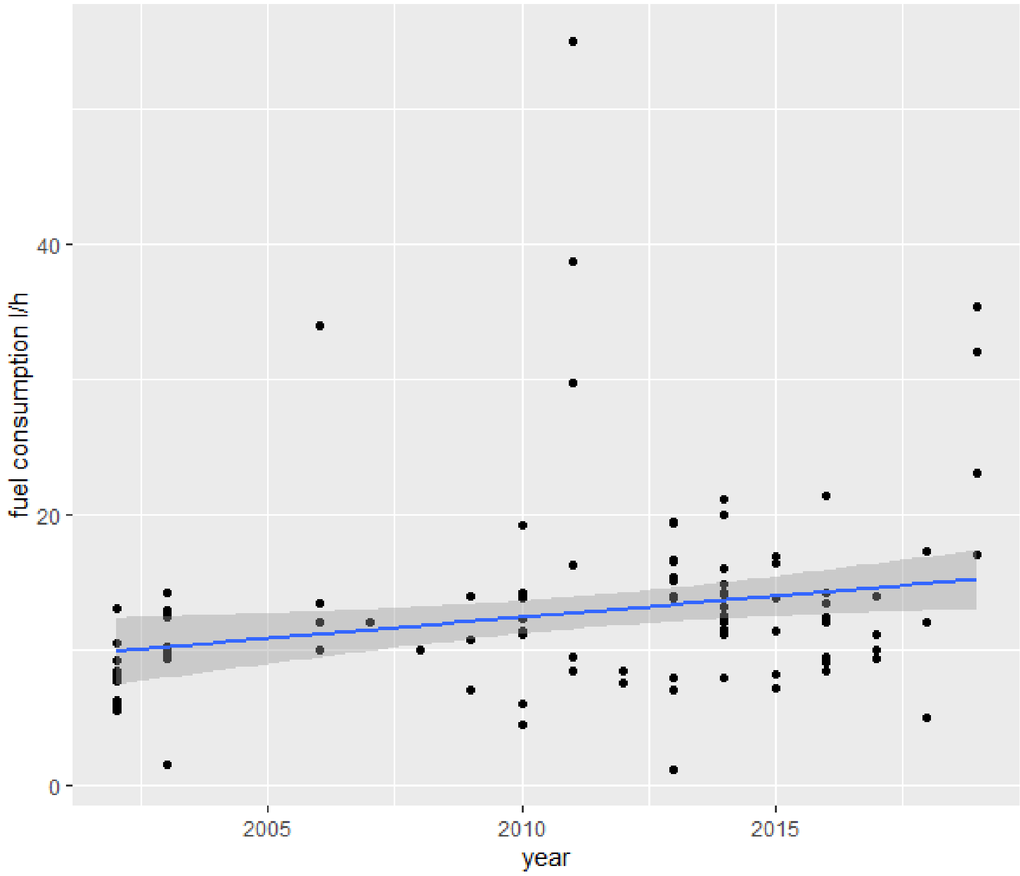

Figure 22 - Forwarder's fuel consumption over time (year weighted by machine's power)

4.2.5 Skidder

96 values of fuel consumption were register for the skidders. NA values are quite high for skidder's productivity, around 75% and power, 47% of the total. Skidder showed to have an average 117.6 kW power output and being able to extract 14.1 m3 of timber consuming 15.1 litres of fuel on a one-hour shift.

Table 12 - Skidder's summary

	Power (kW)	**Productivity (m^3/PMH)**	**Fuel consumption (l/PMH)**	**Fuel consumption (l/m^3)**	**CO_2 equ (kg/PMH)**	**CO_2 equ (kg/m^3)**
Minimum	37.0	3.200	1.300		3.473	
1st quartile	101.5	5.697	7.963		21.270	
Median	126.4	11.148	12.037		32.154	
Mean	117.6	14.085	15.139	1.769	40.440	4.723
3rd quartile	138.0	16.591	19.285		51.514	
Maximum	171.6	72.00	58.730		156.880	
NA's	45 /96 (47%)	71/96 (74%)	/96		/96	
Standard deviation	34.52806	13.71891	10.23943		27.35158	

The regression lines show how fuel consumption is directly proportional to both power and productivity (Figure 23 and figure 24)

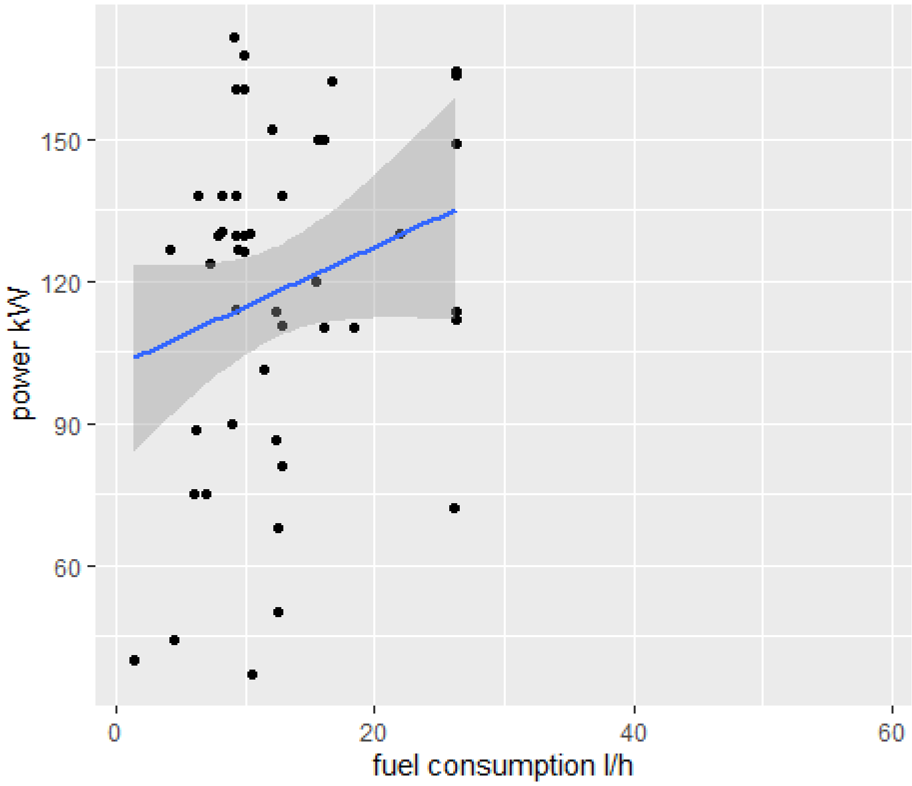

Figure 23 - Regression line of skidder's power (kW) and fuel (l/PMH)

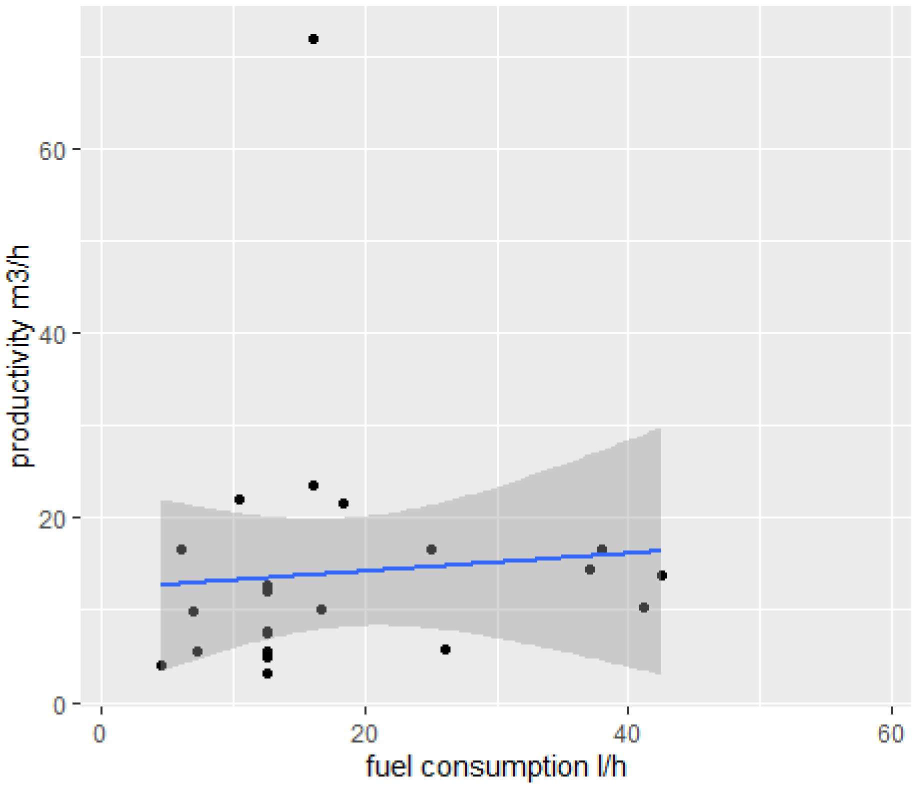

Figure 24- Regression line of skidder's productivity and fuel

In table 13 the correlation values are listed for power, productivity and fuel.

Table 13- Skidder's correlation values

Correlations	**Fuel**	**Power**
Power	0.361456	/
Productivity	0.2191047	0.3580212

The fuel consumption of skidders is explained by power ad productivity as follows:

$$FC = 2.56349204 + 0.08621835 * productivity + 0.09586202 power$$

Where:

FC = fuel consumption in l/PMH

Productivity = harvesting productivity in m³/PMH

Power = machine power in kW

Skidder showed an increased fuel consumption rate over time according to the data gathered in this study.

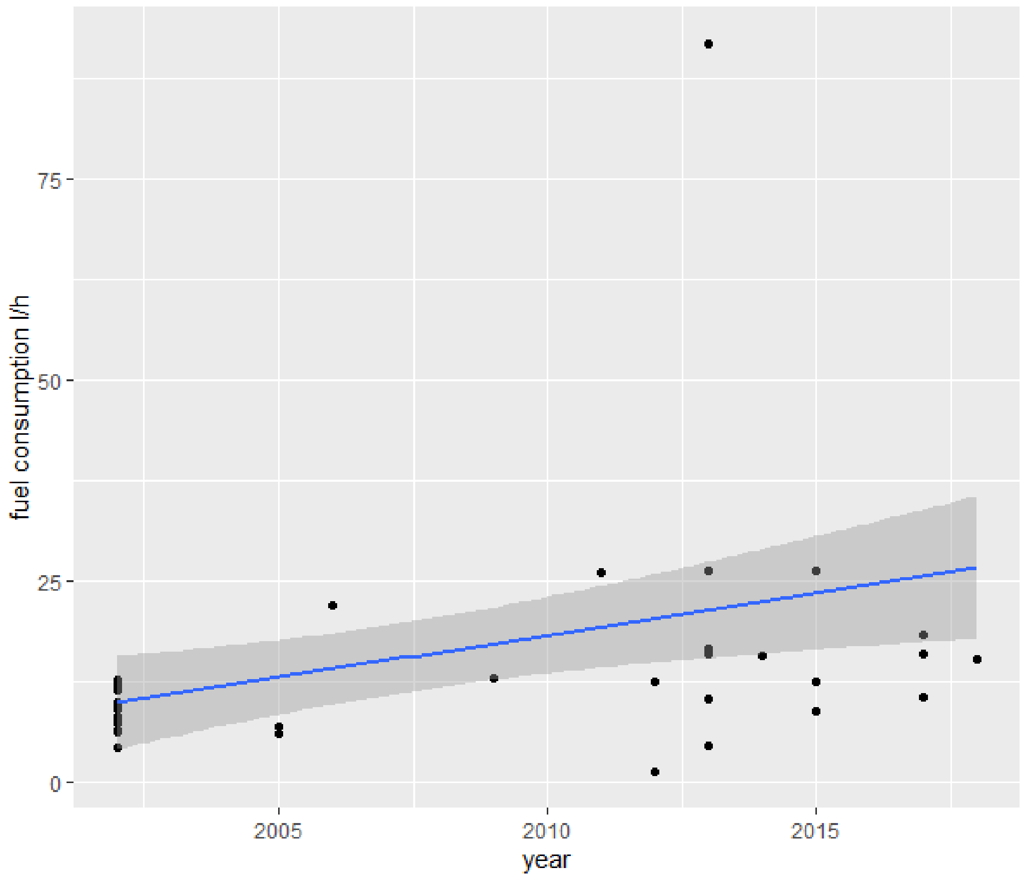

Figure 25 - Skidder's fuel consumption over time (year weighted by machine's power)

4.2.6 Tractor

A total of 54 values have been registered under this machine type. The average fuel consumption was registered to be 13.5 l/PMH and 1.709 m³/l. The NA values are quite high and homogeneous for both power and productivity at 56%.

Table 14 - Tractor's summary

	Power (kW)	Productivity (m^3/PMH)	Fuel consumption (l/PMH)	Fuel consumption (l/m^3)	CO_2 equ (kg/PMH)	CO_2 equ (kg/m^3)
Minimum	40.0	0.810	2.04		5.449	
1st quartile	78.5	4.625	6.45		17.229	
Median	85.0	6.410	8.00		21.370	
Mean	86.2	7.793	10.22	1.7093	27.298	4.563
3rd quartile	97.0	10.082	13.50		36.061	
Maximum	120.0	19.450	23.61		63.067	
NA's	30/54 (56%)	30/54 (56%)	/54		/54	
Standard deviation	16.66623	5.027113	5.829698		15.57229	

Figure 26 and 27 represents the regression lines of power and productivity as regards for tractors.

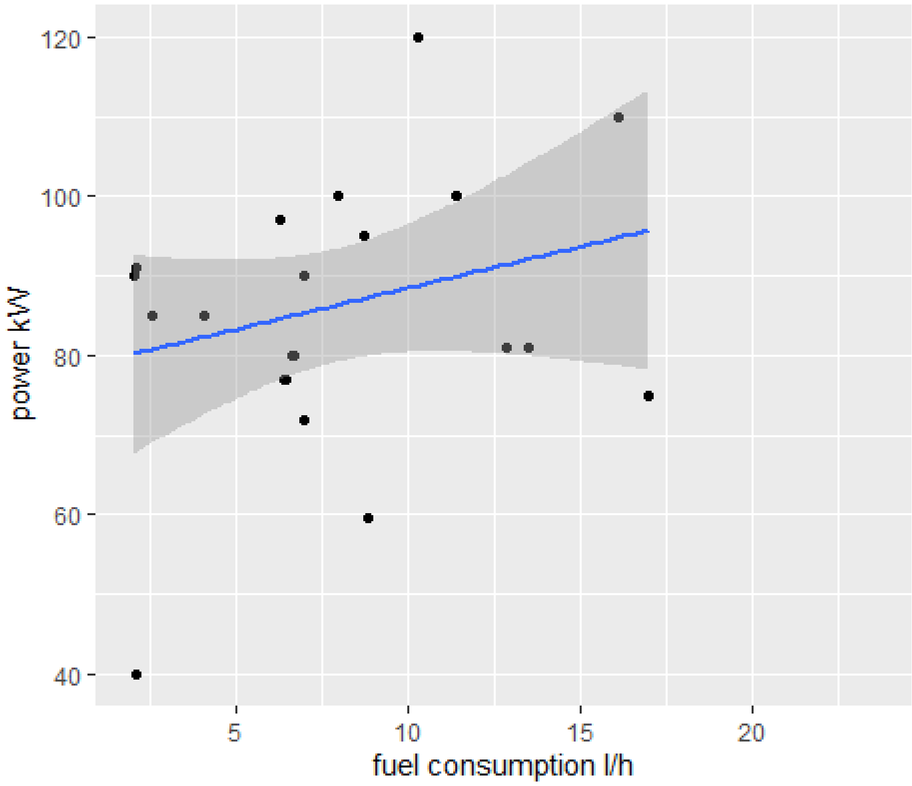

Figure 26 - Regression line of tractor's power (kW) and fuel (l/PMH)

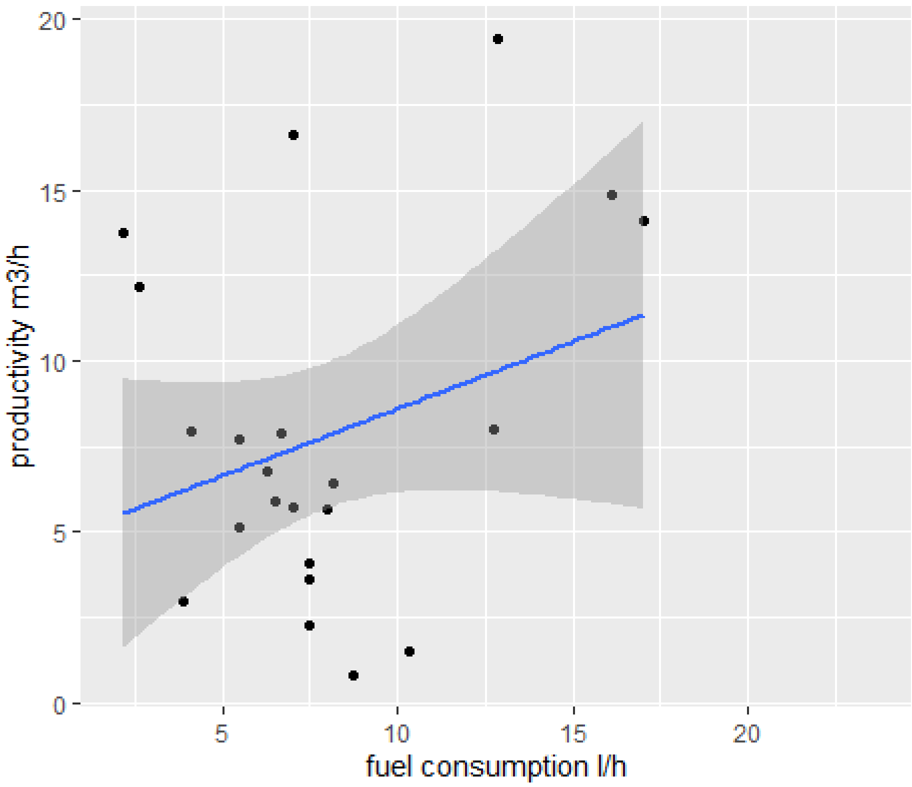

Figure 27 - Regression line of tractor's productivity and fuel

In the following table (Table 15) the correlation values are shown for power, productivity and fuel.

Table 15 - Tractor's correlation values

Correlations	Fuel	Power
Power	0.0730275	
Productivity	0.1306623	-0.09518717

The following equation represents the linear model that's explain the fuel consumption of tractors depending to productivity and power.

$$FC = 6.23150999 + 0.12529897 * productivity + 0.03153684 * power$$

Where:

FC = fuel consumption in l/PMH

Productivity = harvesting productivity in m^3/PMH

Power = machine power in kW

In the last figure of this section fuel consumption is plotted to highlight it trend over time.

Figure 28 - Tractor's fuel consumption over time (year weighted by machine power)

4.2.7 Excavator

22 studies reported data about excavators. Excavators are part of this study because, even if they're not specifically designed for forestry equipment, they're largely used in forestry as they can be used in forestry simply adding a proper head on top of the boom, harvesting head to cut trees or a simple grapple to load and stock logs. The average power of these machines coming from the building industry stated around 96.73 kW being able to process approximately 11.53m^3 of wood consuming 17.92 litres of fuel in one hour. The NA values of power and productivity were quite low, being both of them under the one third threshold.

Table 16 - Excavator's summary

	Power (kW)	Productivity (m^3/PMH)	Fuel consumption (l/PMH)	Fuel consumption (l/m^3)	CO_2 equ (kg/PMH)	CO_2 equ (kg/m^3)
Minimum	40.30	5.10	10.84		28.96	

1st quartile	80.25	8.95	14.30		38.20	
Median	103.0	10.60	17.90		47.81	
Mean	96.73	11.53	17.92	1.46	47.86	3.89
3rd quartile	115.75	14.40	22.50		60.10	
Maximum	127.00	18.60	25.43		67.93	
NA's	3/22 (13%)	6/22 (27%)	/22		/22	
Standard deviation	23.77344	4.051361	4.785078		12.7819	

The regression lines are here represented (Figure 29 and Figure 30) and their results are sustained by the values reported in table number 15.

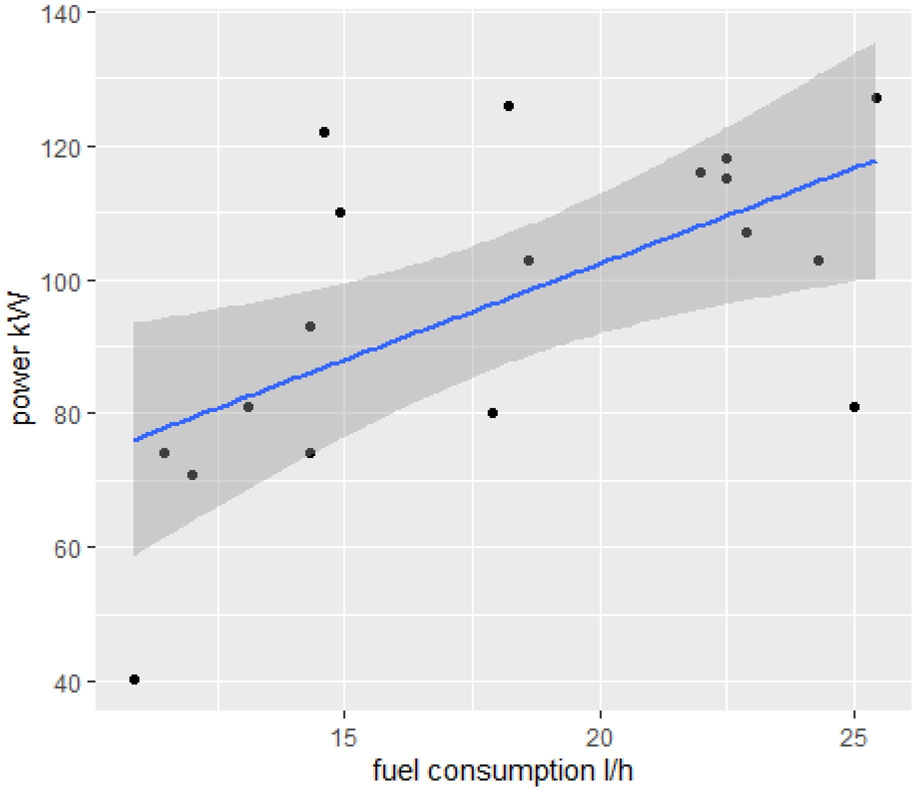

Figure 29 - Regression line of excavator's power and fuel

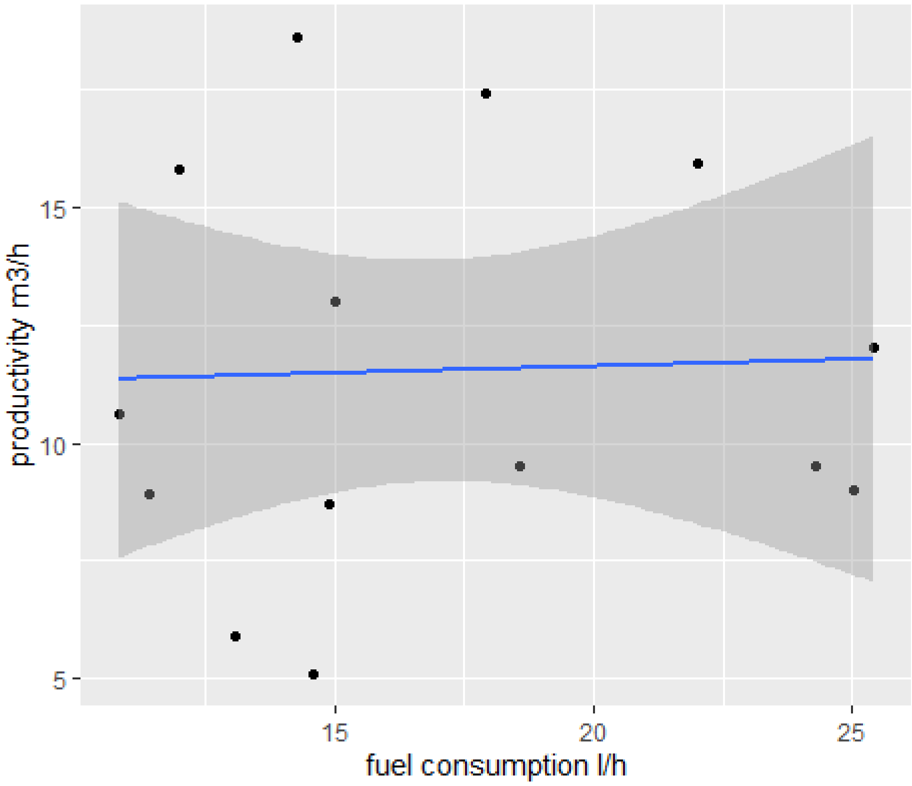

Figure 30- Regression lines of excavator's productivity and fuel

Table 17 - Excavator's correlation values

Correlations	**Fuel**	**Power**
Power	0.6340467	
Productivity	-0.02162387	-0.3097404

The model here represented shows how the power and productivity of the loaders affects their fuel consumption.

$$FC = 1.2252687 + 0.2519236 * productivity + 0.1445717 power$$

Where:

FC = fuel consumption in l/PMH

Productivity = harvesting productivity in m^3/PMH

Power = machine power in kW

The fuel consumption over time of the loaders is almost unchanged.

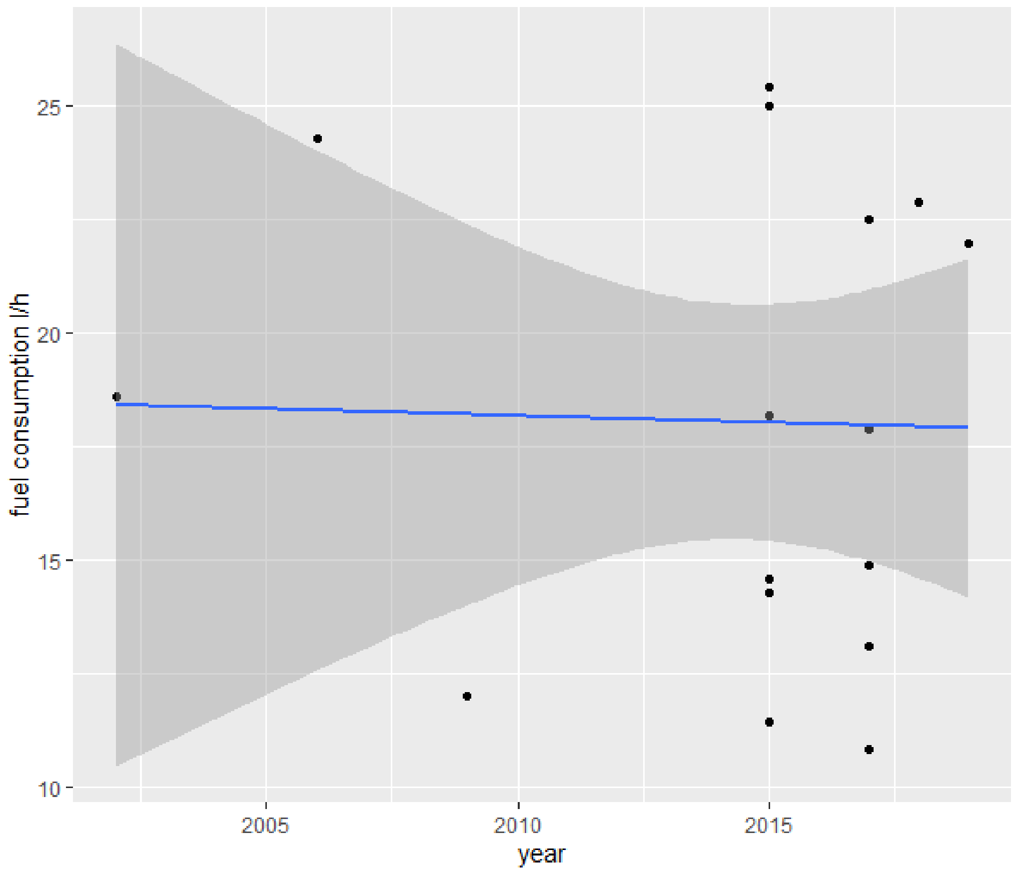

Figure 31 - Excavator's fuel consumption over time (year weighted by machine's power)

4.2.8 Loader

47 loaders' studies were analysed and an extremely high level of NA values (89%) was registered for productivity paired with a slightly less one for power, recording only 25% of NA values. Loaders, with an average power of 120 kW, can process (stacking, sorting and loading) 42.06 m^3 of timber every hour matching the highest productivity of every machines. The fuel consumed in one hour by these machines is around 12.6 litres.

Table 18 - Loader's summary

	Power (kW)	**Productivity (m^3/PMH)**	**Fuel consumption (l/PMH)**	**Fuel consumption (l/m^3)**	**CO_2 equ (kg/PMH)**	**CO_2 equ (kg/m^3)**
Minimum	57.0	35.56	4.751		12.69	
1st quartile	110.4	39.34	6.159		16.45	
Median	119.2	41.32	9.481		25.33	
Mean	120.1	42.06	12.568	1.31	33.57	3.51

3rd quartile	129.8	44.04	18.929		50.56	
Maximum	199.9	50.05	30.000		80.14	
NA's	12/47(25%)	42/47(89%)	/47		/47	
Standard deviation	27.56897	6.006166	7.415756		19.80897	

The regression lines showed, where the data quality allowed, a positive correlation between fuel and both power and productivity. (Figure 32 and Figure 33) Their values are, on the other hand, represented by table number 19.

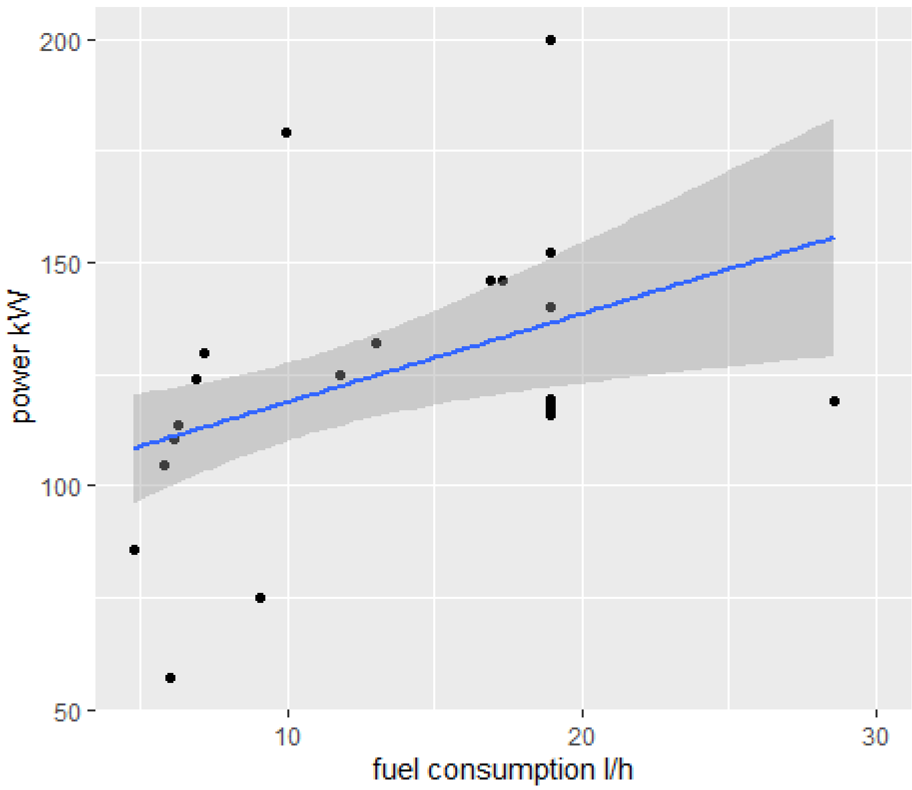

Figure 32 - Regression line of loader's power and fuel

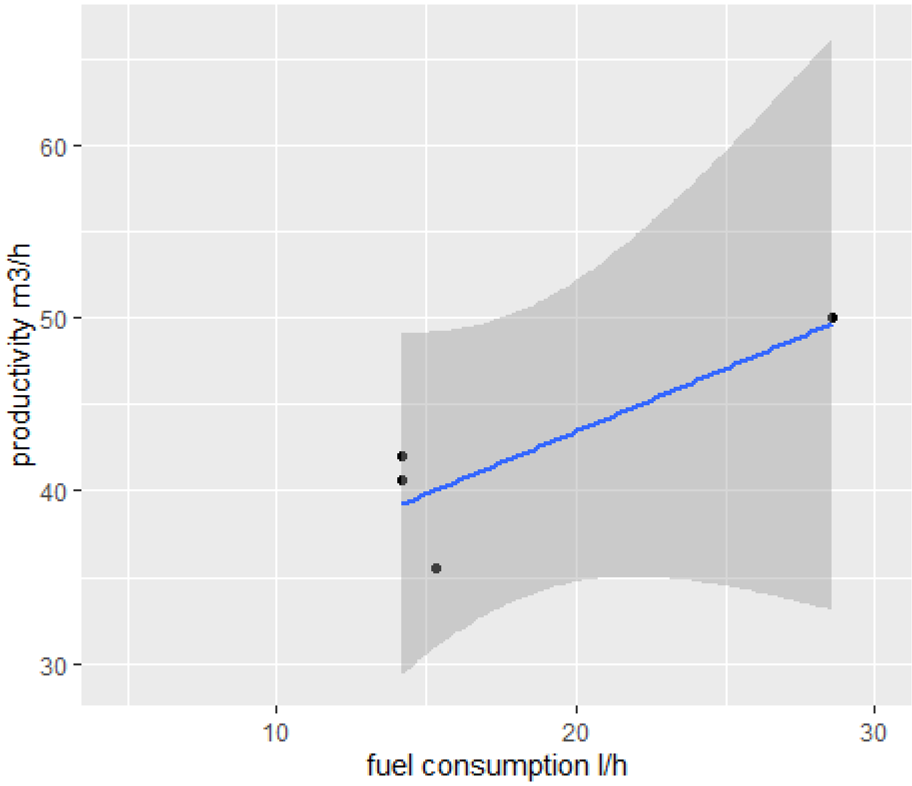

Figure 33 - Regression line of loader's productivity and fuel

Table 19 - Loader's correlation values

Correlation	**Fuel**	**Power**
Power	0.376917	
Productivity	-0.1699352	-0.03706756

Fuel consumption is described, linearly, by productivity and power as follow for loaders.

$$FC = 10.44043509 - 0.22746776 * productivity + 0.09288847 power$$

Where:

FC = fuel consumption in l/PMH

Productivity = harvesting productivity in m^3/PMH

Power = machine power in kW

In figure 34 the loader's fuel consumption instead is shown over time as recorded by this study.

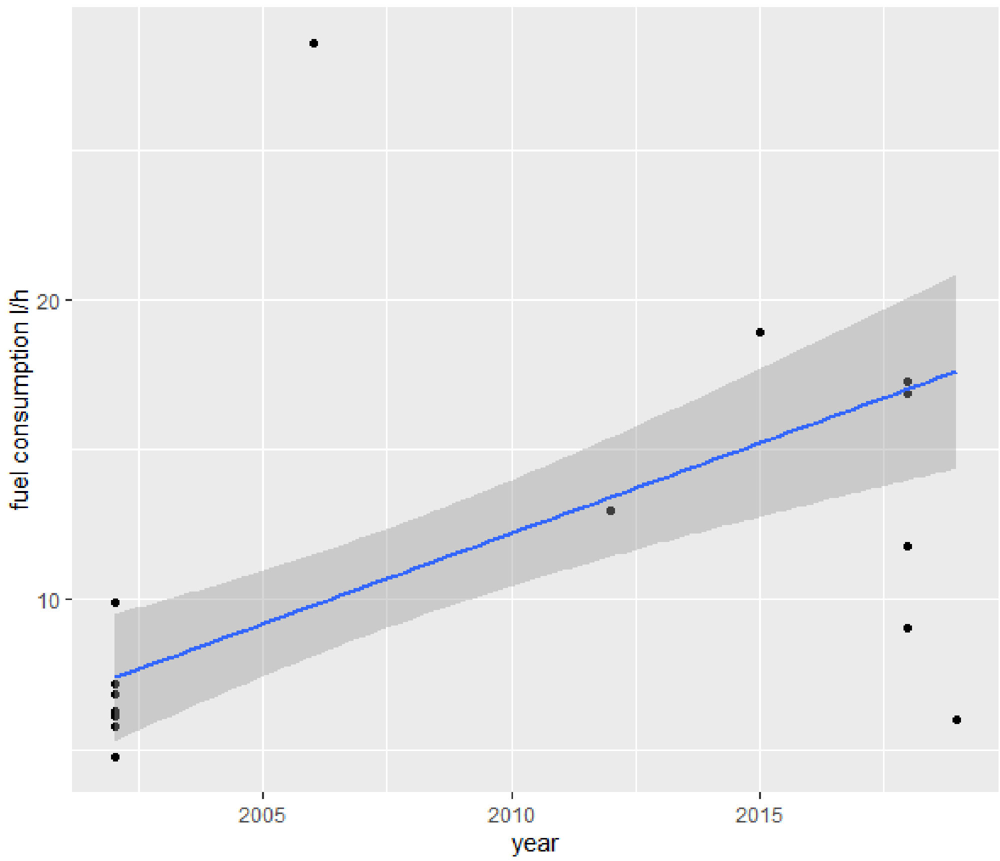

Figure 34 - Loader's fuel consumption (l/PMH) over time (year weighted by machine's power)

4.2.9 Chipper

A total of 64 data were recorded for the chipper section. The machine, that reported the highest variability with every variable, reported an average power of 266.6 kW able to process an average of 48.15 m^3 of timber every hour and consuming, on an hourly basis 36.5 litres of fuel. These values locate chippers among the first places for all the variables analysed. The NA values registered in this section were 29% and 35% for productivity and power respectively.

Table 20 - Chipper's summary

	Power (kW)	**Productivity (m^3/PMH)**	**Fuel consumption (l/PMH)**	**Fuel consumption (l/m^3)**	**CO_2 equ (kg/PMH)**	**CO_2 equ (kg/m^3)**
Minimum	55.0	4.44	3.528		10.58	
1st quartile	188.8	26.00	21.15		63.45	
Median	235.5	41.05	34.00		102.00	
Mean	266.8	48.15	36.485	1.06	109.46	3.18

3rd quartile	351.2	64.50	45.575		136.72	
Maximum	450.0	150.00	72.600		217.80	
NA's	23/64 (35%)	19/64 (29%)	/64		/64	
Standard deviation	115.0992	32.91998	18.3477		55.0431	

The work studied the regression also, showing a positive correlation between fuel and power and productivity respectively (Fig. 35 and 36).

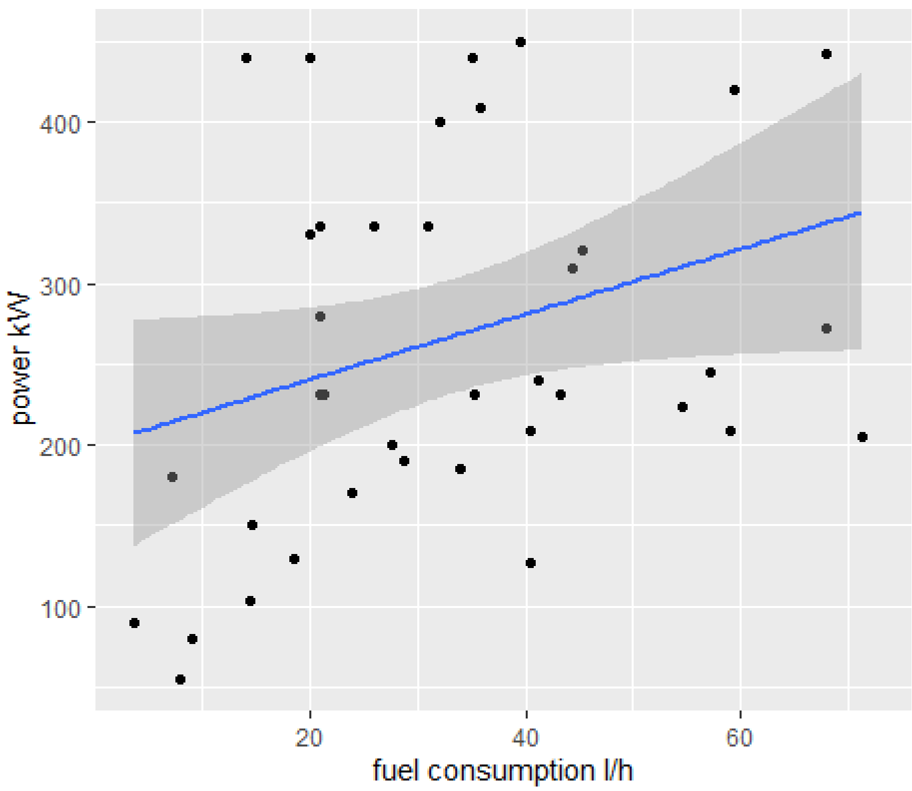

Figure 35 - Regression line of chipper's power and fuel

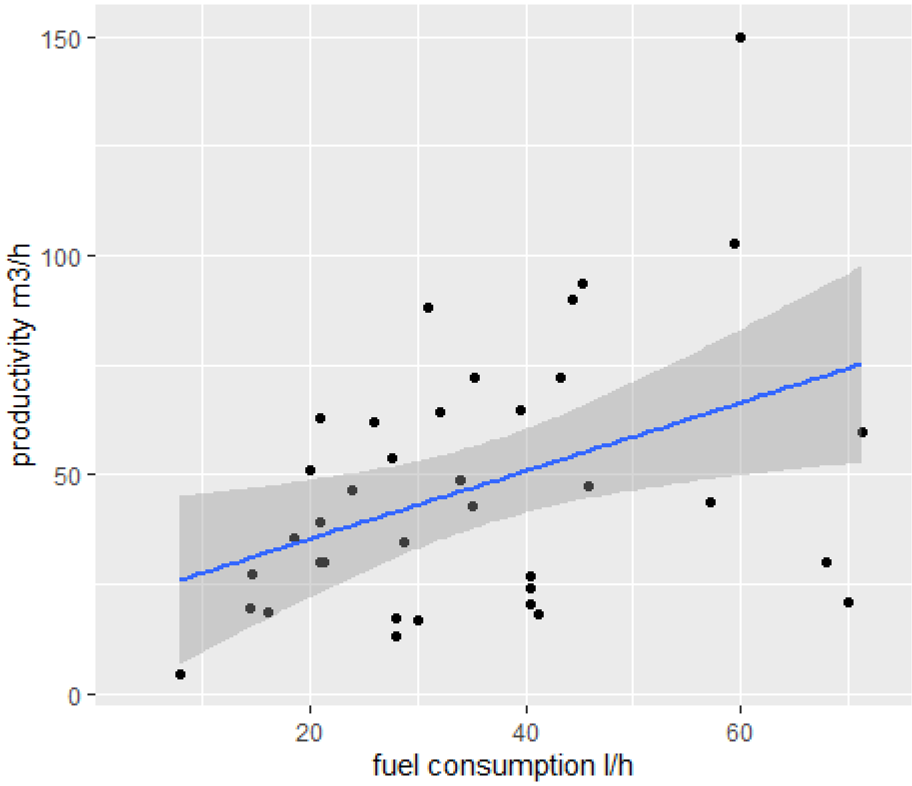

Figure 36 - Regression line of chipper's productivity and fuel

Table 21 confirmed and measured what graphically visible with the regression lines of the abovementioned figures (Figure 35 and Figure 36).

Table 21 - Chipper's correlation values

Correlations	**Fuel**	**Power**
Power	0.2533858	/
Productivity	0.3101554	0.6560098

The equation here represents shows the how the fuel consumption is described by both productivity and power output.

$$FC = 26.46325328 + 0.13198287 * productivity + 0.01470343 power$$

Where:

FC = fuel consumption in l/PMH

Productivity = harvesting productivity in m³/PMH

Power = machine power in kW

Fuel consumption trend over time highlights a consistent decrease as shown in figure 37.

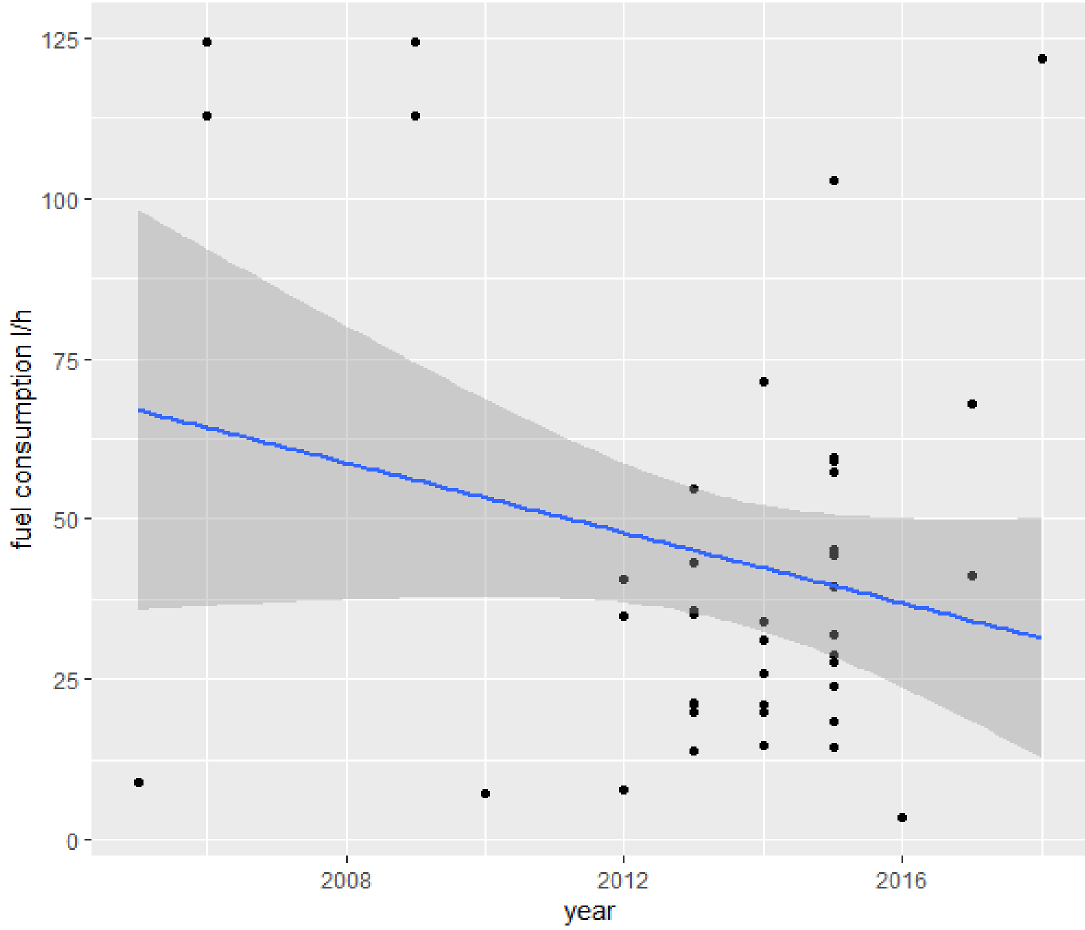

Figure 37 - Chipper's fuel consumption over time (year weighted by machine's power)

5 DISCUSSION

A great number of publications went under analysis while making this thesis, showing how important and studied forest operations' sustainability became over the last decades (Klein, 2015). The datasets for each machine provide handy and useful tools for further researches and following up studies that are surely needed.

The first thing that is made clear by the datasets is that, regardless of the intense work made on the data quality, all the datasets appeared to be in some cases not sufficient to be able to produce any reliable data. In particular, the values that are lacking the most are "power" and "productivity" variables, showing with certain machines, an extremely low amount of data compared to the total values reported for fuel consumption, as fuel data were the one that was set to be the benchmark as it was the most reported variables among the studies gathered for this work.

The first reason was related to the fact that studies reporting this kind information are relatively recent and most importantly because most of the studies reporting this kind of information are LCA studies and report the emissions for operations and not for single machines (i.e. Gonzalez-Garcia, 2013).

Secondly, analysing the datasets another assumption was easy to take: some machines have higher importance compared to others. Since these two machines combined totalized approximately a third of the total values analysed in this work, clearly harvester and forwarder are the most studied machines as are widely used all over the world being almost the only one used in the Scandinavian countries and in a good portion of the southern hemisphere's countries (Bronisz, 2018; Spinelli, 2006). Different argument for harwarders and slash-bundlers that appeared to be the least analysed machines. Both machines are extremely specific and for this reason, used only in some extremely rare cases (Bronisz, 2018), or because with some substantial technical limitations that made not economically convenient to use them (personal communication, Boku 2019).

5.1 Descriptive statistics

In general, all the machines showed results as expected by this work but it's important to point out a few aspects that appeared while dealing with the descriptive statistic of some machines.

As a measure of unit for the data quality is important to look at the NAs values for each variable. The higher the percentage of NAs values the lower the data quality for that given variable. As the main database was constructed starting from fule consumption data no NAs values are recorded in that section, different story for machine power, productivity that appear to be the most neglected values in the database and literature in general. The problem got worse when analysis involving those variables were needed. NAs values higher than the 50% affect the validity and reliability of the datas.

Chippers appeared to be the biggest machine and the one with the highest variability in the power and, subsequently, in the productivity sector. This is explained by the extremely high variability of machine types that are built to try to occupy the bigger share of market, using different power output as chippers can be self powered, can use truck's engine or can be attached to tractor's PTO.

Another important aspect to highlight is related to loader's data, in particular the productivity's mean values. This, in fact, can be biased as in some cases loaders are used to load or sort logs, increasing the difference of values according to the activity that the machine carried on. The productivity of loaders, strangely appeared to be quite homogeneous as the same machine is normally used both for loading and stacking having these two processes different productivity levels and in most cases was not specified whether the data was referred to a machine sorting or loading.

Forwarders and harvesters appear to be the most studied machines and on the other side slash bundlers and harwarders the least studied ones. Important to mentions also how trucks have been left outside the statistical analysis for the same reason.

As regards for tractors is important to highlight that some tractors are machines initially designed with different purpose and subsequently modified into forest machines, this couldn't be shown in the results as the engine most of the times is the same for both sector.

5.2 Models

Unfortunately, the models listed in the results section can't really be used as the R-squared values and R-adjusted ones are too low in most of the cases as they must stay around 0.5 or higher (Schmuller, 2017). The number of values registered for the excavator's section is too low for any reliable data to run a linear model but it has been calculated anyway. This, again clearly shows how the data gathered aren't complete enough to provide valuable data.

The models were initially thought to be both for fuel and CO_2 emissions but for the reason mentioned above models for emissions weren't reliable and for this reason were not included in this work.

5.3 Fuel consumption trends

The fuel consumption trends highlighted, once again, the poor quality of the dataset, in particular both loaders and excavators showed really poor results as the fuel consumption weighted by the machine powers' data were really a few, not enough to consider the data reliable.

Another notable aspect of this analysis is that forwarders, harvesters and skidders show an increasing fuel consumption over time, going against the trend showed by the other machines and against the expectations (Internal Boku communication, 2019). The rest of the machines, indeed, show a little to big decrease in fuel consumption as expected. These two results may show that in same cases engines are becoming more and more efficient but not the most used machines and this need, for sure, further researches.

6 CONCLUSION

The final objective of this work was to create a database, as complete as possible reporting fuel and emission data for some selected machine involved in forest operations, performing an LCI study as defined by the ISO 14044. The appendixes show all the more than seven hundred fuel values that have been gather highlighting how this sector is gaining importance even if it's changing its objectives and the major direction of studies (Wang, 2004; Klein et al., 2015 and Duka, 2017).

Descriptive statistic implemented on the dataset highlighted the difference between diesel driven machines and the only one fuelled by gasoline, the chainsaw, as the context is completely different.

Another objective that this thesis' work aimed to obtain was a series of models to express fuel consumption based on the power and/or productivity data of the machines. From these models will be easy to assess also emission data simply using a conversion factor. As wrote in the discussion part not all machines fitted the requirements to run a linear model regression and for this reason not included in the results part.

The trends researched over time for each machine showed interesting results as the two mostly used machines, harvester and forwarder, were efficiency it is supposed to be firstly and highly implemented, showed indeed an increase of fuel consumption over time. On the other hand, less represented machines described a decrease in fuel consumption from 2000 to date.

What became clear while setting the data for the statistics part is the extremely heterogenous type of fuel, productivity and emission data. This is mainly explained by the type of publication these values come from as different objectives because, as easily shown in the first appendix, this work gathered a lot of different type of articles. One example is given by those studies labelled as LCA that reported the fuel consumption levels per hectare per year and it was, in most cases, impossible to transform them into the given measure unit. A way to solve this impediment can be given by normalizing the process of data gathering. The eventual protocol should keep the way of how you get those data as simple as possible and trying to avoid as much as possible stops in the operating process. This affected, obviously, the data quality has been affected by the lack of data in some key areas damaging this whole work.

Luckily in the last years a lot of new technologies have been developed to monitor the machines' performances, increasing the availability of data in a less cost intensive manner. Hopefully they'll be implemented by the forest workers and contractors themselves in order to create a way bigger dataset and to have highly reliable data for further researches.

Further researches are what this topic surely needs but the work itself might be useful for other scientists as it creates a data pool all forestry related research's topic. The author, beyond the appendixes where all the databases are, offers his work for further studies in all works forms.

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7.2 Sitography

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7.3 List of figures

7.4 List of tables

7.5 Abbreviations

A lot of abbreviations have been used in the making of this thesis. They can be easily divided into two mains subgroups: the ones reported in the databases and the ones showed in the prosaic part of the thesis. The abbreviations reported in the Rstudio’s code lines are not reported here as made up for time management purposes and without any scientific value.

For the ones referred to the type of publication:

ACC = Accessory, referred to the type of publication described. It reports accessory data of a study.
E = Emissions, referred to the study type. The research studied emission data.
e = emissions, in the study emission data were found
f = fuel, in the study fuel data were found

LCA = Life Cycle Analysis, referred to the study type
P = performance, referred to the study type. The study described performances of a/multiple machine/s
S = Survey, referred to the type of publication. The data come from a survey
SRF = Short Rotation Forestry, the research is located within the framework of the short rotation forestry.

As regards for the machine's abbreviations:

t = tracked
w = wheeled, preceded by the number of wheel drive
h = harvester
fb = feller buncher
cs = cable skidder
gs = grapple skidder
PMH = Productive machine hours, productivity measure unit
PMH15 = Productive machine hours considering time delays up to 15 minutes, productivity measure unit
E = productivity measure unit
E15 = productivity measure unit considering time delays up to 15 minutes
SMH = Scheduled machine hours

8 DATABASES

8.1 All publications and machine categories

Author, year	Pub. Type	Cable Yarder	Chainsaw	Chipper	Excavator	Forwarder	Harvester	Hardwarder	Loader	Skidder	Slash bundler	Tractor	Truck	Field data	Wood/timber data
Abbas, 2014	S		f	f	f	f	f	f	f	f			f	Y	N
Abbas, 2018	LCA		f/e				f/e		f/e	f/e			f/e	Y	Y
Ackerman, 2016	P					f	f							Y	N
Ackerman, 2017	E					f/e	f/e							Y	Y
Alam, 2011	E			f/e		f/e	f/e						f/e	N	N
Apafalan, 2017	P					f	f							Y	Y
Aruga, 2011	E	f/e	f/e	f/e								f/e	f/e	Y	Y
Asikainen, 2011	ACC			f		f	f							N	N
Assirelli, 2013	P			f										Y	Y
Athanassiadis, 2000	E					f/e	f/e							N	N
Bacenetti, 2016	SRF			f/e										Y	Y
Becker, 2011	ACC		f						f	f				Y	Y
Berendt, 2018	P									f/e				Y	Y
Berg, 2003	E		f/e			f/e	f/e					f/e		N	N
Berg, 2012	E		f/e			f/e	f/e			f/e				N	N
Blouin, 2013	E						f/e			f/e				Y	Y
Bodaghi, 2018	P		f							f				Y	Y
Boku task, 2019	PC	f	f	f		f	f			f		f		N	N

Author, year	Pub. Type	Cable Yarder	Chainsaw	Chipper	Excavator	Forwarder	Harvester	Hardwarder	Loader	Skidder	Slash bundler	Tractor	Truck	Field data	Wood/timber data
Brinker, 2002	S					f	f		f	f				N	N
Cerutti, 2014	LCA		f/e									f/e		Y	Y
Colantoni, 2016	P		f											N	N
Cremer, 2017	ACC			f		f								Y	Y
Danilovic, 2011	P						f							Y	Y
De la Fuente, 2016b	LCA					f/e			f/e					Y	Y
Dembure, 2019	ACC		f			f	f		f			f		Y	Y
Devlin, 2013	E												f/e	N	N
Di Fulvio, 2017	ACC		f		f		f							N	N
Dias, 2007	E		f/e			f/e	f/e					f/e		N	Y
Dimou, 2018	E		e											N	N
Do Nascimento Santos, 2016	E				f/e									N	N
Dodson, 2015	S						f		f	f				N	N
Eliasson, 2018				f										Y	Y
Ellis, 2019	E									e		e		Y	Y
Enache, 2013	ACC									f				Y	Y
Enache, 2015	S	f/e	f/e			f/e	f/e			f/e		f/e		N	N
Engel, 2012	E		f/e			f/e	f/e					f/e		N	N
England, 2013	LCA					e	e						e	Y	N
Engler, 2016	ACC					f	f							Y	N
Eriksson, 2006	E					e	e							N	Y
Eriksson, 2007	E					f/e	f/e							Y	Y

Author, year	Pub. Type	Cable Yarder	Chainsaw	Chipper	Excavator	Forwarder	Harvester	Hardwarder	Loader	Skidder	Slash bundler	Tractor	Truck	Field data	Wood/timber data
Gasol, 2009	LCA						f/e							N	Y
Gerasimov, 2012	ACC						f							Y	Y
Ghaffariyan, 2013	P			f					f					Y	Y
Ghaffariyan, 2013b	P			f			f			f				Y	Y
Ghaffariyan, 2015	P					f	f							Y	Y
Ghaffariyan, 2016	P			f										Y	Y
Gonzalez-Garcia, 2013	LCA					f	f			f				N	Y
Gonzalez-Garcia, 2014	LCA					f	f							N	Y
Greene, 2014	S						f		f	f				N	N
Gustavsson, 2011	E			f/e		f/e							f/e	N	N
Handler, 2014	S		f/e			f/e	f/e			f/e			f/e	N	N
Holzleitner, 2010	P	f				f	f			f				N	N
Holzleitner, 2011	P	f				f	f			f				N	N
Ignea, 2016	P		f											Y	N
Jappinen, 2003	E						e							Y	N
Jappinen, 2013	E												e	Y	Y
Jappinen, 2013b	E												e	N	N
Johnson, 2005	LCA	f					f			f				N	N

Author, year	Pub. Type	Cable Yarder	Chainsaw	Chipper	Excavator	Forwarder	Harvester	Hardwarder	Loader	Skidder	Slash bundler	Tractor	Truck	Field data	Wood/timber data
Jourgholami, 2013	P		f											N	Y
Kaleja, 2018	P					f								Y	Y
Kaleja, 2018b	ACC			f		f	f						f	N	N
Karha, 2013	P						f							Y	Y
Karha, 2018	P					f	f							Y	Y
Kenney, 2014	P					f	f		f	f				N	N
Khiza, 2016	P						f		f					Y	Y
Kilpelainen, 2011	LCA				f/e	f/e	f/e						f/e	Y	Y
Klein, 2016	LCA		f/e			f/e	f/e					f/e		N	N
Klepac, 2013	P									f				N	Y
Klugmann, 2006	PC		f											N	N
Klvac, 2003	P					f	f							N	N
Klvac, 2009	P				f	f	f							N	N
Klvac, 2012	S	f/e							f/e			f/e		N	N
Klvac, 2013	S												f/e	N	Y
Koutsianitis, 2017	P		f/e										f/e	Y	Y
Laitila, 2010	ACC			f		f	f						f	Y	Y
Laitila, 2015	P			f								f		N	Y
Laitila, 2015b	P			f										N	Y
Laschi, 2016	LCA	f/e	f/e	f/e	f/e							f/e		N	N
Lijewski, 2013	E						e							Y	Y
Lijewski, 2017	E					f/e	f/e						f/e	N	Y

Author, year	Pub. Type	Cable Yarder	Chainsaw	Chipper	Excavator	Forwarder	Harvester	Hardwarder	Loader	Skidder	Slash bundler	Tractor	Truck	Field data	Wood/timber data
Lindholm, 2007	LCA												f/e	Y	N
Lindroos, 2014	P					f	f							N	Y
Liska, 2010	P			f/e										N	Y
Liska, 2011	E										f/e			N	N
Lovarelli, 2018	LCA		f/e				f/e					f/e		Y	N
Maesano, 2013	LCA		f						f	f		f		N	N
Magagnotti, 2011	ACC											f		Y	N
Magagnotti, 2013	P			f	f							f		Y	Y
Magagnotti, 2017	P				f		f							Y	Y
Malkki, 2002	E					e	e			e			e	Y	Y
Manzone, 2009	ACC						f							N	N
Manzone, 2013	SRF			f										Y	Y
Manzone, 2013b	ACC			f										Y	Y
Manzone, 2015	SRF			f/e										Y	Y
Manzone, 2018	P								f/e					N	N
Markewitz, 2006	E	f/e				f/e	f/e			f/e				N	N
May, 2012	S			e			e							Y	Y
Mederski, 2013	P		f			f	f							Y	Y

Author, year	Pub. Type	Cable Yarder	Chainsaw	Chipper	Excavator	Forwarde r	Harvester	Hardward er	Loader	Skidder	Slash bundler	Tractor	Truck	Field data	Wood/ti mber data
Mihelic, 2015	P			f										Y	Y
Mousavi, 2011	P		f											Y	Y
Nati, 2014	ACC			f										N	Y
Nordfjell, 2003	P					f								Y	Y
Ottar, 2006	LCA					f/e	f/e						f/e	Y	Y
Ozturk, 2006	P	f												Y	Y
Ozturk, 2009	P	f												Y	Y
Palander, 2016	S						f							N	N
Pandur, 2018	P					f								Y	Y
Pergola, 2018	E		f/e	f/e								f/e		Y	Y
Picchio, 2012	P			f			f		f					Y	Y
Pierobon, 2015	LCA		e									e	e	Y	Y
Pochi, 2013	P			f										Y	Y
Prada, 2015	P			f/e										Y	Y
Prinz, 2018	P						f/e							Y	Y
Proto, 2015	P	f												Y	Y
Proto, 2017	LCA	f/e	f/e							f/e		f/e		Y	Y
Proto, 2017b	LCA	f/e	f/e							f/e		f/e		Y	Y
Proto, 2018	P									f				Y	Y
Puttock, 2013	P					f	f							Y	Y
Roeser, 2012	P			f					f					N	N
Rotensteiner, 2008	P					f								Y	Y
Routa, 2012	LCA			f/e	f/e	f/e	f/e						f/e	N	Y
Rozitis, 2017	P					f								Y	Y
Sabo, 2005	P									f				Y	Y

Author, year	Pub. Type	Cable Yarder	Chainsaw	Chipper	Excavator	Forwarder	Harvester	Hardwarder	Loader	Skidder	Slash bundler	Tractor	Truck	Field data	Wood/timber data
Sanchez-Garcia, 2016	P					f								Y	Y
Schweier, 2015	P				f									Y	Y
Schweier, 2016	SRF						f/e							Y	Y
Schweier, 2017	LCA											f		Y	Y
Senturk, 2007	P	f												Y	Y
She, 2018	P						f		f	f				Y	Y
Spinelli, 2002	P				f									Y	Y
Spinelli, 2006	DR			f	f	f	f		f	f		f		N	Y
Spinelli, 2010	P					f						f		Y	Y
Spinelli, 2011	ACC	f	f			f	f					f		Y	Y
Spinelli, 2012	P									f				Y	Y
Spinelli, 2012b	ACC			f										N	Y
Spinelli, 2013	P			f			f			f				Y	Y
Spinelli, 2014	S			f										Y	N
Spinelli, 2014b	P							f						Y	Y
Spinelli, 2015	P			f										Y	Y
Spinelli, 2015b	P					f						f		Y	Y
Spinelli, 2018	E			f/e										Y	Y
Spinelli, 2019	E				f/e									N	N
Stawicki, 2016	ACC		f											N	N
Suvinen, 2006	ACC					f								Y	Y
Tahvanainen, 2011	ACC												f	N	N
Talbot, 2005	P						f					f		N	N
Talbot, 2015	P				f									N	N

Author, year	Pub. Type	Cable Yarder	Chainsaw	Chipper	Excavator	Forwarder	Harvester	Hardwarder	Loader	Skidder	Slash bundler	Tractor	Truck	Field data	Wood/timber data
Unknown, 2011	P					f	f	f						N	N
Valente, 2011	LCA	f/e	f/e	f/e	f/e								f/e	Y	Y
Van Belle, 2006	ACC			f/e										N	N
Vangansbenke, 2015	P			f	f	f	f					f		Y	Y
Vusic, 2013	P									f/e				Y	Y
Walsh, 2014	P					f	f							Y	Y
Yoshida, 2014	P			f										Y	Y
Yoshioka, 2000	P					f								Y	Y
Yoshioka, 2005	P			f/e		f/e	f/e							Y	Y
Yu, 2017	ACC			f	f					f				N	N
Zhang, 2015	LCA		f/e			f/e	f/e						f/e	N	N
Zhang, 2017	P													N	N

8.2 Machine categories

8.2.1 Cable Yarders

		Machine spec					Consumption
Author, year	Pub. Type	Maker	Model	Power	Type	Productivity	Fuel
Aruga, 2011	E				Swing yarder	3,85-2,25-1,58m3/PMH	13,0l/PMH
Aruga, 2011	E				Tower Yarder	10,97-7,56-5,77m3/PMH	3,0l/PMH
Aruga, 2011	E				Yarder	4,56-3,94-3,62m3/PMH	2,8l/PMH
Enache, 2015	S						13,3l/PMH
Holzleitner, 2010	P	MM Forsttechnik	10	170-330kW			5,3-16,0-24,8l/PMH
Holzleitner, 2010	P	MM Forsttechnik	16	170-330kW			5,3-16,0-24,8l/PMH
Holzleitner, 2010	P	MM Forsttechnik	5	170-330kW			5,3-16,0-24,8l/PMH
Holzleitner, 2010	P	MM Forsttechnik	5	170-330kW			5,3-16,0-24,8l/PMH
Holzleitner, 2010	P	MM Forsttechnik	3 to	170-330kW			5,3-16,0-24,8l/PMH
Holzleitner, 2010	P	MM Forsttechnik		170-330kW	Truck mounted		5,3-16,0-24,8l/PMH
Johnson, 2005	LCA			large		7,78100ft3/SMH	1,80gal/100ft3
Johnson, 2005	LCA			large		10,79100ft3/SMH	1,19gal/100ft3
Klvac, 2012	S	Larix	500		Tractor mounted	6000m3/y	1,2l/m3
Klvac, 2012	S	Larix	3T		Tractor mounted	6000m3/y	1,4l/m3

Laschi, 2016	LCA			104kW		6,2st.m3/PMH	3,26kg/PMH
Markewitz, 2006	E	TLD Gauthier Inc	TL-3000	53kW			27+6l/PMH
Ozturk, 2006	P	Gartner		34kWW		6,225m3/PMH	3,5l/PMH
Ozturk, 2009	P	Urus	MIII	120kW	Mounted on Unimog	10,08m3/PMH	3,75l/PMH
Proto, 2015	P	Koller	K300	45kW		2,79-3,30m3/PMH	7l/PMH
Proto, 2015	P	Greifenberg	VSG 2000	69kW		2,37-2,48m3/PMH	10l/PMH
Proto, 2015	P	Greifenberg	TG 700	84kW		2,53-2,87m3/PMH	13l/PMH
Proto, 2017				175kW	trailer mounted	6,9m3/PMH	16,24kg/PMH
Proto, 2017b	LCA			85kW		55,2m3/d	16,2kg/PMH
Senturk, 2006	P	Koller	K300	38kW	Tractor mounted		2,3l/PMH
Spinelli, 2011	ACC						6,6E/PMH
Valente, 2011						9,57m3/PMH	4l/PMH
Valente, 2011						7,42m3/PMH	5l/PMH
Boku task, 2019	PC	TST	400			3,32m3/PMH	16l/PMH
Boku task, 2019	PC	MM Forsttechnik	Turmfalke			4,66m3/PMH	16l/PMH
Boku task, 2019	PC	MM Forsttechnik	Wanderfalke			4,47m3/PMH	16l/PMH

		Emission	**Site spec**		**Wood spec**	
Author, year	**Lubrificants**	**CO2**	**Slope**	**Extracting d**	**Extraction t.**	**Spp.**
Aruga, 2011		for HS	>30degrees	100-200-300	WT	Cedar, Cypress, broadleaves
Aruga, 2011		for HS	>30degrees	100-200-300	WT	Cedar, Cypress, broadleaves
Aruga, 2011		for HS	>30degrees	100-200-300	WT	Cedar, Cypress, broadleaves

Enache, 2015		35,6kg/PMH				
Holzleitner, 2010	3,6-12,9-32,2%fuel cost					
Holzleitner, 2010	3,6-12,9-32,2%fuel cost					
Holzleitner, 2010	3,6-12,9-32,2%fuel cost					
Holzleitner, 2010	3,6-12,9-32,2%fuel cost					
Holzleitner, 2010	3,6-12,9-32,2%fuel cost					
Holzleitner, 2010	3,6-12,9-32,2%fuel cost					
Johnson, 2005	0,03gal/100ft3	for HS			Thinning	
Johnson, 2005	0,02gal/100ft3	for HS			Clearcut	
Klvac, 2012	1,7kg/1000m3					
Klvac, 2012	1,7kg/1000m3					
Laschi, 2016			Av. 22%	270m	SWS/WTH	Oak spp., ash, maple
Markewitz, 2006		for HS				
Ozturk, 2006			75% w/ >40%			Picea, Abies, Fagus
Ozturk, 2009			75% w/ >40%			Picea, Abies, Fagus
Proto, 2015	0,22l/PMH		Av. 64-59%	315-200	SW	Oak spp.
Proto, 2015	0,34l/PMH		Av. 75-78%	530-260	FT	Oak spp.
Proto, 2015	0,4l/PMH		Av. 68-75%	250-280	TL	Beech spp.
Proto, 2017			Av. 60%			Chestnut
Proto, 2017b		for HS			WT	roundwood
Senturk, 2006			Av. 53,3%			

Spinelli, 2011			40%-60%	150-180-250		
Valente, 2011					WTS	
Valente, 2011					STS	
Boku task, 2019						
Boku task, 2019						
Boku task, 2019						

8.2.2 Chainsaw

		Machine spec					**Consumption**	
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**		**Productivity**	**Fuel**	**Lubrificants**
Abbas, 2014	S					For HS	4,16l/PMH	
Abbas, 2018	LCA					For HS	13,8l/PMH	4,6l/PMH
Abbas, 2018	LCA					For HS	12,6l/PMH	4,2l/PMH
Aruga, 2011	E					FORMULA	2,8l/PMH	
Aruga, 2011	E					2,0m3/PMH	2,8l/PMH	
Becker, 2011	ACC	Stihl	441	4,2kW		5,0tons/PMH	0,75gal/PMH	
Becker, 2011	ACC	Stihl	441	4,2kW		9,5tons/PMH	1,01gal/PMH	
Becker, 2011	ACC	Stihl	460	4,5kW		7,0tons/PMH	0,77gal/PMH	
Becker, 2011	ACC	Stihl	460	4,5kW		7,0tons/PMH	0,77gal/PMH	
Becker, 2011	ACC	Husqvarna	372	4,0Kw		7,0tons/PMH	0,9gal/PMH	
Berg, 2003	E					4,91m3/PMH	0,53l/PMH	
Berg, 2012	E						For HS	
Bodaghi 2018	P	**Stihl**	ms880	6,4kW			1,50USD/PMH	
Boku Task, 2019		Husqvarna	365XPG			5,75m3/PMH	0,53l/PMH	
Cerutti, 2014	LCA			2,6kW		740kg/PMH	0,64kg/PMH	0,5kg/PMH

Cerutti, 2014	LCA			2,6kW			0,64kg/PMH	0,5kg/PMH
Cerutti, 2014	LCA			3,4kW			0,64kg/PMH	0,5kg/PMH
Dembure, 2019	ACC	Stihl	MS440				0,47l/PMH	20% fuel
Di Fulvio, 2017	ACC	Husqvarna	550XP	2,8kW			0,9l/PMH	
Di Fulvio, 2017	ACC			4,9kW			0,9l/PMH	
Di Fulvio, 2017	ACC			4,0kW			0,9l/PMH	
Di Fulvio, 2017	ACC	Stihl	MS461	4,4kW			0,9l/PMH	
Di Fulvio, 2017	ACC			4,0kW			0,9l/PMH	
Dias, 2007	E						1l/PMH	
Dias, 2007	E						1l/PMH	
Dimou, 2018	E	Stihl	361MS					
Dimou, 2018	E	Stihl	170MS					
Dimou, 2018	E	Makita	CCS4301					
Enache, 2015	S					2,2-4,3-8,4m3/PMH	1,5l/PMH	
Engel, 2012	E					2,50m3/PMH	1,5l/PMH	0,6l/PMH
Handler, 2014	S					For HS	1,1+-0,6l/PMH	
Ignea, 2016	P	**Husqvarna**	365XP	3,6kW			To calculate?	
Ignea, 2016	P	**Stihl**	362	3,4kW			To calculate?	
Johnson, 2005	LCA					2,49100ft3/SMH	0,08gal/100ft3	
Jourgholami, 2013	P	**Stihl**			4hp	362ft3/PMH	13USD/PMH	=
Klein, 2016	LCA					2,07m3/PMH*2,87m3/PMH	1,7*2,4l/PMH	
Klein, 2016	LCA					2,9m3/PMH*4,07m3/PMH	1,7*2,4l/PMH	
Klein, 2016	LCA					3,1m3/PMH*5,7m3/PMH	1,7*2,4l/PMH	
Klein, 2016	LCA					2,57m3/PMH*3,9m3/PMH	1,7*2,4l/PMH	
Klugmann, 2006		Dolmar	115i	2,7			0,806l/PMH	0,394l/PMH
Klugmann, 2006		Dolmar	6400	3,5			1,15l/PMH	0,6l/PMH
Klugmann, 2006		Dolmar	7900	4,7			1,112l/PMH	0,50l/PMH

Klugmann, 2006		Husqvarna	346	2,7			0,745l/PMH	0,245l/PMH
Klugmann, 2006		Husqvarna	357	3,2			0,956l/PMH	0,40l/PMH
Klugmann, 2006		Husqvarna	372	3,9			0,90l/PMH	0,393l/PMH
Klugmann, 2006		Stihl	66	5,2			1,726l/PMH	0,73l/PMH
Klugmann, 2006		Stihl	260	2,6			0,63l/PMH	0,30l/PMH
Klugmann, 2006		Stihl	360	3,4			1,155l/PMH	0,45l/PMH
Klugmann, 2006		Stihl	361	3,4			1,02l/PMH	0,43l/PMH
Klugmann, 2006		Stihl	460	4,5			1,106l/PMH	0,42l/PMH
Koutsanitis, 2017	P	Stihl	MS440	4		8,64-1,96m3/PMH	2,4l/PMH	0,36E/PMH
Laschi, 2016	LCA			3,5kW		8,50m3/PMH	1,13kg/PMH	0,56kg/PMH
Laschi, 2016	LCA			3,5kW		19,9m3/PMH	0,93kg/PMH	0,46kg/PMH
Lijewski, 2013	E			2,5kW	50,2cm3	1 harvester=4 chainsaws	0,38dm3/PMH	
Lovarelli, 2018	LCA						32,1kg/PMHa	16,0kg/PMHa
Maesano, 2018	LCA	Stihl	MS880	6,4kW		To calculate	To calculate	To calculate
Mederski, 2013	P	Husqvarna	346XP			8,58m3/PMH	0,35l/PMH	
Mousavi, 2011	P	**Stihl**	MS 880			35m3/PMH	0,5US/PMH	
Oekl, 2019				2kW			0,7l/PMH	
Oekl, 2019				3,5kW			1,16h/l	
Oekl, 2019				5kW			1,55l/PMH	
Pergola, 2018	LCA	**Husqvarna**	Rancher II 455	2,6			2,1kg/PMH	
Pierobon, 2015	LCA			3,6kW				
Proto, 2017	LCA						1,0kg/PMH	0,5kg/PMH
Proto, 2017b	LCA			4,8kW		74,1m3/d	1,0kg/PMH	=
Spinelli, 2011	ACC						0,5E/PMH	
Stawicki, 2016	ACC	**Husqvarna**	357XP				Over m2 (surface)	
Valente, 2011								

Zhang, 2015	LCA					4,06ton/PMH	To calculate	

	Emission	**Site spec**		**Wood spec**	
Author, year	**CO2**	**Slope**			
Abbas, 2014				CC/SW/SC	
Abbas, 2018				H+S	
Abbas, 2018	For HS			H+S	
Aruga, 2011	For HS			WT	Japanese cedar, Japanese Cypress
Aruga, 2011	For HS			WT	Broadleaves
Becker, 2011			409trees/ac	Sawlogs and pulpwood	
Becker, 2011			236trees/ac	Sawlogs and pulpwood	
Becker, 2011			134tress/ac	Sawlogs and pulpwood	
Becker, 2011			134tress/ac	Sawlogs and pulpwood	
Becker, 2011			212trees/ac	Sawlogs and pulpwood	
Berg, 2003	For HS				Pine, Spruce
Berg, 2012	For HS				Maritime pine and eucalypt
Bodaghi 2018		25%-39%	286,4-225,8stem/PMHa		Beech, Hornbeam - Silver fir, beech
Boku Task, 2019					
Cerutti, 2014					
Cerutti, 2014	For HS				
Cerutti, 2014	For HS				
Dembure, 2019		0-12%/12-20%		TL/CTL	Pinus eliotii
Di Fulvio, 2017				TH	
Di Fulvio, 2017					
Di Fulvio, 2017					
Di Fulvio, 2017					

Di Fulvio, 2017					
Dias, 2007				Coppice selection	
Dias, 2007	839gCO2/m3-541gCO2/m3			TH	Eucalypt, Maritime Pine
Dimou, 2018	To calculate				
Dimou, 2018	To calculate				
Dimou, 2018	To calculate				
Enache, 2015	3,5kg/PMH			CTL/TH	
Engel, 2012	168,28kgeq.CO2				Spruce
Handler, 2014				CC/SW/SC	
Ignea, 2016				TL	
Ignea, 2016				TL	
Johnson, 2005	For HS				
Jourgholami, 2013					
Klein, 2016	For HS			SW/IW/SL*TH/FF	Spruce
Klein, 2016	For HS			SW/IW/SL*TH/FF	Pine
Klein, 2016	For HS			SW/IW/SL*TH/FF	Beech
Klein, 2016	For HS			SW/IW/SL*TH/FF	Oak
Klugmann, 2006					Spruce
Klugmann, 2006					Spruce, beech
Klugmann, 2006					Beech
Klugmann, 2006					Beech
Klugmann, 2006					Spruce, beech, oak, fir
Klugmann, 2006					Spruce
Klugmann, 2006					Beech
Klugmann, 2006					Beech, spruce, oak, fir
Klugmann, 2006					Oak
Klugmann, 2006					Spruce

Klugmann, 2006					Spruce, beech, fir
Koutsanitis, 2017		Mild to medium/steep		TL/WA	Pinus Sylvestris, Picea Abies
Laschi, 2016	For HS			SWS/WTH	Oak spp., ash, maple
Laschi, 2016	For HS			SWS/WTH	Oak spp., ash, maple
Lijewski, 2013	2,68g/m3 (CO)				
Lovarelli, 2018	For HS	Flat		Roundwood	Poplar
Maesano, 2018	To calculate		36trees/PMHa		Sapelli, Frake'
Mederski, 2013		0%	300trees/PMHa		
Mousavi, 2011					
Oekl, 2019					
Oekl, 2019					
Oekl, 2019					
Pergola, 2018					
Pierobon, 2015	0,17gCO2eq				Beech
Proto, 2017					
Proto, 2017b		30%-43%-60%		WTH	
Spinelli, 2011		0-20/40-60/20-40			
Stawicki, 2016					Beech
Valente, 2011	For HS			Wood chips	
Zhang, 2015	For HS			SC/SW/CC	

8.2.3 Chipper

		Machine spec			
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**
Abbas, 2014	S				

Alam, 2011	E				
Aruga, 2011	E				Mobile
Aruga, 2011	E				Mobile
Asikainen, 2011	ACC				Mobile
Asikainen, 2011	ACC				Mobile
Asikainen, 2011	ACC				Mobile
Assirelli, 2013	P	Pezzolato Hacker	PTH-700/660	231kW (Case MX 270)	PTO powered
Assirelli, 2013	P	Pezzolato Hacker	PTH-700/661	231kW (Case MX 270)	PTO powered
Boku Task, 2019	PC	**Silvatec**	878CH		Purpose built
Boku Task, 2019	PC	**Jenz HEM**	35D		Truck mounted
Boku Task, 2019	PC	**MUS MAX**	Woodterminator 10		Truck mounted
Boku Task, 2019	PC	**Starchl**	1200-800		Truck mounted
Boku Task, 2019	PC	**Jenz Hem**	561R		Truck mounted
Cremer, 2017	ACC	Erjofant	7/65 RC	272kW	Forwarder mounted
Cremer, 2017	ACC			442kW (Man Truck)	Truck mounted
Eliasson, 2018		**Bruks**	806STC	368kW (Scania engine)	Truck mounted
Ghaffariyan, 2013	P	**Morbark**	B12		
Ghaffariyan, 2013b	P	**Husky Precision**	HTC 2366		
Ghaffariyan, 2016	P	**Bruks**	805.2	223.8 kW	Forwarder mounted
Ghaffariyan, 2016	P	**Peterson**			Truck mounted
Gustavsson, 2010	E				
Gustavsson, 2011	E				
Kaleja, 2018b	ACC	**Bruks/timberjack**	1001/1410	336kW/136kW	Mounted on TJ 1410
Laitila, 2010	ACC				Truck mounted
Laitila, 2010	ACC				Truck mounted
Laitilla, 2015	P	**Kesla**	C1060A	559kW (Volvo FH750)	Truck mounted

Laitilla, 2015	P	**Kesla**	C4560LF	209kW (Valtra S280)	PTO powered
Laschi, 2016	P			90kW	PTO powered
Liska, 2010	LCA	Jenz Hem	420D	180kW(Fendt Vario 716)	PTO powered
Magagnotti, 2013	P	Pezzolato	PTH12000/1000	440kW	Truck mounted
Magagnotti, 2013	P	Pezzolato	PTH12000/1001	440kW	Truck mounted
Manzone, 2013	SRF	**John Deere/Pezzolato**	7700	409kW	Forager chipper
Manzone, 2015	SRF			103kW	Feller chipper/pto
Manzone, 2015	SRF			130kW	c/pto
Manzone, 2015	SRF			170kW	c
Manzone, 2015	SRF			190kW	Feller chipper/pto
Manzone, 2015	SRF			200kW	c
Manzone, 2015	SRF			310kW	c
Manzone, 2015	SRF			320kW	g
Manzone, 2015	SRF			420kW	Feller chipper
May, 2012	S				
Mihelic, 2015	P	Albach	Silvator 2000	450kW	Dedicated chipper
Nati, 2014	ACC	Jenz Hem	561	264kW (Claas Xerion)	PTO powered
Nati, 2014	ACC	Jenz Hem	561	264kW (Claas Xerion)	PTO powered
Nati, 2014	ACC	TS	1200	174kW (JD810D)	Forwarder mounted
Nati, 2014	ACC	TS	1200	174kW (JD810D)	Forwarder mounted
Pergola, 2018	E	**Iveco**	CIP2300		Truck mounted
Picchio, 2012	P	**Erjo**		440+118kW	Mounted on JD1100
Pochi, 2013	P	**Pezzolato**	PTH 700/660	231kW	Tractor powered
Pochi, 2013	P	**Pezzolato**	PTH 700/660	231kW	Tractor powered
Prada, 2015	P	**Pezzolato Hacker**	900/660	320hp	
Prada, 2015	P	**Mus Max**	Terminator 7		

Prada, 2015	P	**Jenz Hem**	561D		
Roeser, 2012	P	Kesla	C4560	209kW (Valtra S280)	PTO powered
Roeser, 2012	P	Kesla	C4560	126,8kW (JD 7920)	PTO powered
Routa, 2012	LCA				large scale drum chipper
Spinelli, 2006	DR			588kW	Disc chipper
Spinelli, 2006	DR			535kW	Drum chipper
Spinelli, 2009	P			588kW	Integral
Spinelli, 2009	P			535kW	Joined
Spinelli, 2012b	ACC	**CRM**		55kW	Tractor powered
Spinelli, 2014	S	**Scania**	460	335kW	Truck mounted
Spinelli, 2014	S	**Valtra**	8450	335kW	PTO powered
Spinelli, 2014	S	**Volvo**	FM12	335kW	Truck mounted
Spinelli, 2014	S	**Claas**	Xerion 4500	330kW	PTO powered
Spinelli, 2014	S	**Claas**	Xerion 3800	280kW	PTO powered
Spinelli, 2014	S	**Deutz**	L730	185kW	PTO powered
Spinelli, 2015	P	**Pezzolato Hacker**	PTH 1200/820	400 Kw	Truck mounted
Spinelli, 2015	P	**Pezzolato Hacker**	PTH 1200/821	400 Kw	Truck mounted
Spinelli, 2015	P	**Pezzolato Hacker**	PTH 1200/820	400 Kw	Truck mounted
Spinelli, 2018	E	**Peterson Pacific**	DDC5000H	839kW (CAT 32 acert)	
Valente, 2011	LCA				
Vangasbenke, 2015	P	Jenz Hem	420	(Valtra T191)	PTO powered
Vangasbenke, 2015	P	Greentec	952	(Valtra N141)	PTO powered
Yoshida, 2014	P	**Yulim Machinery**	400C	150kW	
Yoshida, 2014	P	**HD**	9	205,1kW	
Yoshioka, 2005	P	**Vermeer**	TG 400A		

Yoshioka, 2005	P	**Oikawa Motors**	6BD1 (Isuzu motors)	79,4kW/2200rpm	
Yu, 2017	ACC	**Morbark**	Typhoon	240 kW	

		Consumption		**Emission**	**Site spec**	**Wood spec**
Author, year	**Productivity**	**Fuel**	**Lubrificants**	**CO2**	**Slope**	
Abbas, 2014		54,89l/PMH				CC/SW/SC
Alam, 2011	150m3/PMH	60l/PMH		For HS		
Aruga, 2011	13m3/PMH	28l/PMH		For HS		WT
Aruga, 2011	13m3/PMH	28l/PMH		For HS		WT
Asikainen, 2011		6,2E/m3				
Asikainen, 2011		2,6E/m3				
Asikainen, 2011		1,6E/m3				
Assirelli, 2013	25t/PMH-72m3/PMH	06l/m3				Stem
Assirelli, 2013	11t/PMH-30m3/PMH	0,7l/m3				Top
Boku Task, 2019	17,04m3/PMH	28,00l/PMH				
Boku Task, 2019	20,28m3/PMH	40,48l/PMH				
Boku Task, 2019	20,80m3/PMH	70,00l/PMH				
Boku Task, 2019	24,00m3/PMH	40,48l/PMH				
Boku Task, 2019	26,88m3/PMH	40,48l/PMH				
Cremer, 2017	30m3/PMH	68l/PMH			2%	Sawlogs, pulpwood
Cremer, 2017	30m3/PMH	68l/PMH			5%	Sawlogs, pulpwood
Eliasson, 2018		0,61 l/MWh			flat	
Ghaffariyan, 2013	59.40GMt/PMH0	72.6 l/PMH			flat	
Ghaffariyan, 2013b	58,18GMt/PMH0	72.14l/PMH			flat	
Ghaffariyan, 2016		54.6 l/PMH				
Ghaffariyan, 2016		100 l/PMH				

Gustavsson, 2010		50l/PMH		For HS		
Gustavsson, 2011		9,5l/PMH		For HS		
Kaleja, 2018b	96,5m3 biomass/PMH	68l/PMH-12l/PMH	45g/PMH			
Laitila, 2010	34m3/PMH	42,14l/PMH				WT
Laitila, 2010	34m3/PMH	42,14l/PMH				Delimbed stemwood
Laitilla, 2015	31184kg/PMH	3,3l/1000kg dry mass				
Laitilla, 2015	19509kg/PMH	3,1l/1000kg dry mass				
Laschi, 2016	8,7t/PMH	4,2kg/PMH				SWS/WTH
Liska, 2010	2,45t/PMH	7,18l/PMH		11125g/FU		
Magagnotti, 2013	13,3t/PMH	20l/PMH				Salvage
Magagnotti, 2013	14,7t/PMH	14l/PMH				Salvage
Manzone, 2013	24-33greent/PMH	25l/SMH				
Manzone, 2015	19,33m3/PMH	14,36l/PMH		3,24kgCO2/m3		Branchwood/WT
Manzone, 2015	27,67m3/PMH-43,00m3/PMH	17,45l/PMH-19,40l/PMH		2,74-1,94		Branchwood/WT
Manzone, 2015	37,67m3/PMH-55,33m3/PMH	22,52l/PMH-25,05l/PMH		2,72-1,84		Branchwood/WT
Manzone, 2015	,-34,67m3/PMH	,-28,27l/PMH		2,85-3,52		Branchwood/WT
Manzone, 2015	39,33m3/PMH-68,00m3/PMH	25,68l/PMH-29,62l/PMH		2,52-1,84		Branchwood/WT
Manzone, 2015	70,33m3/PMH-110,00m3/PMH	43,32l/PMH-45,50l/PMH		2,41-1,72		Branchwood/WT
Manzone, 2015	75,00m3/PMH-112,67m3/PMH	42,86l/PMH-47,86l/PMH		2,41-1,72		Branchwood/WT
Manzone, 2015	102,67m3/PMH	59,52l/PMH				Branchwood/WT
May, 2012						S/PMH
Mihelic, 2015	161-180m3loose/PMH	0,61l/m3				WT

Nati, 2014		2,78dm3/odt				Logging residues
Nati, 2014		2,26dm3/odt				TH
Nati, 2014		1,68dm3/odt				Logging residues
Nati, 2014		1,66dm3/odt				TH
Pergola, 2018		12,45kg/PMH				
Picchio, 2012	43,1m3/PMH	35l/PMH			flat	Coppice
Pochi, 2013	72m3/PMH	0,59l/m3				Stems
Pochi, 2013	30m3/PMH	0,71l/m3				Tops
Prada, 2015	43,71 m3/PMH	57,21 l/PMH	0,63 l/PMH	7,09kgCO2eq/MWh	5,5	WTH
Prada, 2015	18,82m3/PMH	16,16 l/PMH	0,18 l/PMH	8,41	44	WTH
Prada, 2015	47,54m3/PMH	45,79 l/PMH	0,51 l/PMH	7,6	12	WTH
Roeser, 2012	25-35-20m3/PMH	40,5l/PMH	0,086l/PMH			SS/Pulpwood/WT
Roeser, 2012	25-35-20m3/PMH	40,5l/PMH	0,086l/PMH			SS/Pulpwood/WT
Routa, 2012	150m3/PMH	60l/PMH				TH
Spinelli, 2006	13,3odT/PMH	87l/SH	37% of fuel cost		4-10%	CC
Spinelli, 2006	17,2odT/PMH	79l/SH	37% of fuel cost		4-10%	CC
Spinelli, 2009		87l/SH				
Spinelli, 2009		79l/SH				
Spinelli, 2012b	3t/PMH	7,8dm3/PMH				Logs
Spinelli, 2014	88m3/PMH	31l/PMH				
Spinelli, 2014	62m3/PMH	26l/PMH				
Spinelli, 2014	63m3/PMH	21l/PMH				
Spinelli, 2014	51m3/PMH	20l/PMH				
Spinelli, 2014	39m3/PMH	21l/PMH				
Spinelli, 2014	49m3/PMH	34l/PMH				
Spinelli, 2015	64,5m3/PMH	32dm3/PMH				Lop, tops, sawmill

Spinelli, 2015	64,5m3/PMH	32dm3/PMH				Lop, tops, sawmill
Spinelli, 2015	64,5m3/PMH	32dm3/PMH				Lop, tops
Spinelli, 2018	94-88m3ub/PMH	111,2l/PMH - 132,1l/PMH		3,38 kg/m3 ub		
Valente, 2011	17,03m3/PMH	30l/PMH		5,29kgCO2eq/m3		WTH
Vangasbenke, 2015		33,56l/PMH				WTH/TH
Vangasbenke, 2015		19,19l/PMH				WTH/TH
Yoshida, 2014	23,7m3/PMH	14,6l/PMH				Small scale
Yoshida, 2014	60m3/PMH	71,4l/PMH				Small scale
Yoshioka, 2005		28,04 dm3/PMH		For HS		
Yoshioka, 2005		9,04 dm3/PMH		For HS		
Yu, 2017	18m3/PMH	40,00$/PMH			0-60%	

Author, year	**Species**
Abbas, 2014	
Alam, 2011	Scots Pine, Norway Spruce
Aruga, 2011	Japanese cedar, Japanese Cypress
Aruga, 2011	Broadleaves
Asikainen, 2011	
Asikainen, 2011	
Asikainen, 2011	
Assirelli, 2013	Poplar Neva clone
Assirelli, 2013	Poplar Neva clone
Boku Task, 2019	
Boku Task, 2019	
Boku Task, 2019	

Boku Task, 2019	
Boku Task, 2019	
Cremer, 2017	Norway Spruce
Cremer, 2017	Norway Spruce
Eliasson, 2018	Spruce, Beech
Ghaffariyan, 2013	Radiata Pine
Ghaffariyan, 2013b	Blue gum
Ghaffariyan, 2016	Mallee
Ghaffariyan, 2016	Mallee
Gustavsson, 2010	
Gustavsson, 2011	
Kaleja, 2018b	
Laitila, 2010	
Laitila, 2010	
Laitilla, 2015	Scots pine
Laitilla, 2015	Scots pine
Laschi, 2016	Oak spp., ash, maple
Liska, 2010	
Magagnotti, 2013	Pinus Pinaster
Magagnotti, 2013	Pinus Pinaster
Manzone, 2013	
Manzone, 2015	
Manzone, 2015	
Manzone, 2015	
Manzone, 2015	
Manzone, 2015	
Manzone, 2015	
Manzone, 2015	

Manzone, 2015	
May, 2012	
Mihelic, 2015	
Nati, 2014	Birch and Spruce
Nati, 2014	Birch and Spruce
Nati, 2014	Spruce
Nati, 2014	Spruce
Pergola, 2018	
Picchio, 2012	Eucaliptus
Pochi, 2013	Poplar
Pochi, 2013	Poplar
Prada, 2015	Pinus Pinaster
Prada, 2015	Pinus Radiata
Prada, 2015	Pinus Pinaster
Roeser, 2012	Spruce, Birch, Pine
Roeser, 2012	Spruce, Birch, Pine
Routa, 2012	
Spinelli, 2006	Eucalypt spp.
Spinelli, 2006	Eucalypt spp.
Spinelli, 2009	
Spinelli, 2009	
Spinelli, 2012b	Hybrid Poplar, Black Locust, Sweet chestnut
Spinelli, 2014	
Spinelli, 2014	
Spinelli, 2014	
Spinelli, 2014	
Spinelli, 2014	
Spinelli, 2014	

Spinelli, 2015	Pine, chestnut, poplar
Spinelli, 2015	Spruce, fir, poplar
Spinelli, 2015	Spruce
Spinelli, 2018	Eucaliptus urograndis
Valente, 2011	
Vangasbenke, 2015	Scot Pine
Vangasbenke, 2015	Scot Pine
Yoshida, 2014	Broad;leaves and conifers
Yoshida, 2014	Broad;leaves and conifers
Yoshioka, 2005	Japanes cedar
Yoshioka, 2005	Japanes cedar
Yu, 2017	Beech, aog

8.2.4 Excavator

		Machine spec					
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Track/wheel**	**Head**	**Productivity**
Di Fulvio, 2017	S	**Hitachi**	Zaxis 200LC	118kW	t		
Di Fulvio, 2017	S	**Volvo**	EC210bf	115kW	t		
Do Nascimiento Santos		**Volvo**	EC210bf	107kW	t	Ponsse H7	30,58-29,31-29,42m3/PMH
Kilpelainen, 2011	LCA				t		13m3/PMH
Klvac, 2009		**Samsung/Lako**	150	70,8kW	t		15,8m3/PMH
Laschi, 2016				71kW	t	Komatsu Forest 370	6,9t/PMH
Magagnotti, 2013		**JCB**	JS180NL		t		

Magagnotti, 2017		**Liebherr**	912	80kW	t	Valmet 965II	17,4m3/PMH
Magagnotti, 2017		**Daewoo**	225 NLCV	110kW	t	Zoeggler ZBH70	8,7m3/PMH
Magagnotti, 2017		**JCB**	180	81kW	t	Woody 60H	5,9m3/PMH
Routa, 2012					t		13,00m3/PMH
Schweier, 2015		**Hitachi**	Zaxis 210	122kW	t	GOMAF GD350	5,1m3/PMH
Schweier, 2015		**Cat**	317LN	81kW	t	Cut-tree450	9
Schweier, 2015		**Hitachi**	EX164	74kW	t	Cut-tree450	8,9
Schweier, 2015		**Hitachi**	EX165	74kW	t	Biasi1400	18,6
Schweier, 2015		**Hitachi**	EX135	93kW	t	Biasi1400	45,1
Spinelli, 2002		**Akermann**	EC200	103kW	t	AFM60	9,5m3/PMH
Spinelli, 2006		**Akermann**	EC200	103kW	t	AFM60	9,5m3/PMH
Spinelli, 2019		**Komatsu**	PC200-8	116 kW	t		15,9m3/PMH
Talbot, 2015		**Doosan**	DX210W	127kW	t	Zoeggeler ZBH58	12m3/PMH
Vangansbeke, 2015		**Hyundai**	R145	126kW	t		
Yu, 2017		**John Deere**	75C	54hp	t	Feacon	10,6m3/PMH

	Consumption		**Emission**	**Site spec**	**Wood spec**	
Author, year	**Fuel**	**Lubrificants**	**CO2 eq**	**Slope**		
Di Fulvio, 2017	22,5l/PMH				Pulpwood	Eucalyptus
Di Fulvio, 2017	22,5l/PMH				Pulpwood	Eucalyptus
Do Nascimiento Santos	25,18-23,24-20,25		67,69-62,57-54,52Kg/PMH	2degrees		Eucalyptus
Kilpelainen, 2011	15l/PMH		3,8kg/m3			
Klvac, 2009	12l/PMH			40%		
Laschi, 2016	5,2kg/PMH			<10%	Coppice/firewood	
Magagnotti, 2013	15l/SMH				Salvage	
Magagnotti, 2017	17,9l/PMH					Spruce, Fir, beech

Magagnotti, 2017	14,9l/PMH					Spruce, Fir, beech
Magagnotti, 2017	13,1l/PMH					Pinus Pinaster, Poplar
Routa, 2012	15,00l/PMH					Spruce, Scots pine
Schweier, 2015	10,2l/SMH			35%	Coppice	Oak spp.
Schweier, 2015	17,5l/SMH			10		Chestnut
Schweier, 2015	8l/SMH			2		Poplar
Schweier, 2015	10l/SMH			3		Black Locust
Schweier, 2015	10l/SMH			2	SRF	Poplar
Spinelli, 2002	13l/SMH			2-27-30-53-26%	CC	Eucaliptus Globulosus
Spinelli, 2006	17l/SH			2-27-30-53-26%	CC	Eucaliptus Globulosus
Spinelli, 2019	22l/PMH					Eucalyptus
Talbot, 2015	22,91E/PMH			Av. 22%	WTH/SWS	Eucalypts spp.
Vangansbeke, 2015	18,2l/PMH					Pinus Pinea, Pinus Pinaster
Yu, 2017	8,75$/PMH					Scots Pine

8.2.5 Forwarder

		Machine spec			
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**
Abbas, 2014					
Ackermann, 2016		**Tigercat**	1075B		
Ackermann, 2017		**John Deere**	1710D	160kW	
Ackermann, 2017		**John Deere**	1710D ECO III	160kW	
Alam, 2011					
Alam, 2011					

Apafalan, 2017		**Komatsu**	840.4	130kW	8w
Asikainen, 2011				Mid-sized	
Asikainen, 2011				Mid-sized	
Asikainen, 2011				Mid-sized	
Athanassidis, 2000					
Berg, 2012					
Boku task, 2019					
Brinker, 2002	S	Cat	574	163kW	tyre
Brinker, 2002	S	Franklin-TF	632	116kW	tyre
Brinker, 2002	S	Franklin-TF	670	152kW	tyre
Brinker, 2002	S	Ponsse	S10	122kW	tyre
Brinker, 2002	S	Ponsse	S15	159kW	tyre
Brinker, 2002	S	Ponsse	S16	210kW	tyre
Brinker, 2002	S	Rottne	Rapid 6	125kW	tyre
Brinker, 2002	S	Rottne	Rapid 8	125kW	tyre
Brinker, 2002	S	Rottne	SMV Rapid 6	185kW	tyre
Brinker, 2002	S	Rottne	SMV Rapid 8	185Kw	tyre
Brinker, 2002	S	Timbco	TF820D	260Kw	tyre
Brinker, 2002	S	Timberjack	1010B	110kW	tyre
Brinker, 2002	S	Timberjack	1410	168kW	tyre
Brinker, 2002	S	Timberjack	1710	210kW	tyre
Cremer, 2017		Gremo	950R		
Cremer, 2017		Gremo	950R		
De La Fuente, 2016				150kW	
De La Fuente, 2016				180kW	
Dembure, 2019		**John Deere**	1510E	156kW	8w
Dias, 2007					
Enache, 2015					

Engel, 2012		**John Deere**	810D		
England, 2013					
Engler, 2016					6w
Engler, 2016					6w
Eriksson, 2006					
Eriksson, 2006					
Ghaffariyan, 2015		**Valmet**	890.3		8w
Ghaffariyan, 2015		**Valmet**	890.3		8w
Gonzalez-Garcia, 2013				105kW	
Gonzalez-Garcia, 2013				105kW	
Gonzalez-Garcia, 2013				105kW	
Gonzalez-Garcia, 2013				105kW	
Gonzalez-Garcia, 2013				105kW	
Gonzalez-Garcia, 2013				105kW	
Gonzalez-Garcia, 2013				105kW	
Gonzalez-Garcia, 2013				105kW	
Gonzalez-Garcia, 2013				105kW	
Gonzalez-Garcia, 2013				105kW	
Gonzalez-Garcia, 2013				150kW	

Gonzalez-Garcia, 2013				150kW		
Gonzalez-Garcia, 2014				105kW		
Gonzalez-Garcia, 2014				105kW		
Gonzalez-Garcia, 2014				150kW		
Gonzalez-Garcia, 2014				150kW		
Gonzalez-Garcia, 2014				105kW		
Gonzalez-Garcia, 2014				105kW		
Gustavsson, 2011						
Handler, 2014						
Holzleitner, 2010		Timberjack	1110	82-150		
Holzleitner, 2010		Timberjack	810	82-150		
Holzleitner, 2010		Valmet	840.2	82-150		
Holzleitner, 2010		Ecolog	574	82-150		
Holzleitner, 2010		Valmet	890.3	82-150		
Holzleitner, 2010		Valmet	860.3	82-150		
Holzleitner, 2010		Valmet	840.3	82-150		
Holzleitner, 2010		Timberjack	1410D	82-150		
Kaleja, 2018		**Logbear**	F4000	62kW		
Kaleja, 2018		**Logbear**	F4000	62kW		
Kaleja, 2018b		**John Deere**	810E	100kW		
Kaleja, 2018b		**John Deere**	810D	86kW		
Karha, 2018		John Deere	1210G			

Karha, 2018		Logset	6F GT		
Karha, 2018		Ponsse	Elk		
Kenney, 2014					
Kilpelainen, 2011					
Kilpelainen, 2011					
Klein, 2016				140kW	
Klein, 2016				140kW	
Klvac, 2010				class 1	
Klvac, 2010				class 2	
Klvac, 2010				class 3	
Klvac, 2010				class 1	
Klvac, 2010				class 2	
Klvac, 2010				class 3	
Klvac, 2009		Timberjack	1210	115,6kW	
Klvac, 2009		Timberjack	810B	81,3kW	
Klvac, 2009		Valmet	860	117,8kW	
Klvac, 2009		Logset	540F	91,0kW	
Laitila, 2010					
Lindroos, 2014			Large	190kW	
Lindroos, 2014			Large reduced	190kW	
Lindroos, 2014			Medium	150kW	
Lindroos, 2014			Medium reduced	150kW	
Lindroos, 2014			Medium reduced+trailer	150kW	
Markewitz, 2006		**TimberJack**	1210B		
Markewitz, 2006		**TimberJack**	230A		
Markewitz, 2006		**Kochring**	F-4 DION		fb+trailer
Mederski, 2013		**Vimek**	606		6wd
Mederski, 2013		**Timberjack**	1010B		

Nordfjell, 2003		**Valmet**	890	130kW	8w
Nordfjell, 2003		**TimberJack**	1710	157kW	8w
Nordfjell, 2003		**Timberjack**	1840		
Nordfjell, 2003		**TimberJack**	1710		
Nordfjell, 2003		**Ponsse**	Buffalo S16		
Nordfjell, 2003		**TimberJack**	1210		
Nordfjell, 2003		**TimberJack**	1110		
Nordfjell, 2003		**FMG**	250		
Nordfjell, 2003		**Vimek**	606		
Oekl, 2019				90kW	
Oekl, 2019				125kW	
Oekl, 2019				140kW	
Ottar, 2006					
Pandur, 2018		**Valmet**	840.2	120kW/2200rpm	6w
Puttock, 2013		**Rotobec**	F2000B	87kW	
Rotensteiner, 2008		**Timberjack**	1110D		
Routa, 2012					
Rozitis, 2017		**Pro Silva**	F2/2	175kW	
Sanchez-Garcia, 2016		**Dingo**	AD-8468	89kW	
Sanchez-Garcia, 2016		**Dingo**	AD-2452	141kW	
Spinelli, 2006		**Deutz**	913	89kW	
Spinelli, 2009		**Volvo***	TD73K	187kW	6wd
Spinelli, 2009		**Deutz***	913	89	6wd
Spinelli, 2010		**Entracon Loglander**	LL85	50 kW	8w
Spinelli, 2010		**Entracon LogLander**	LL85	50kW	8W
Spinelli, 2011					

Spinelli, 2014b		**Pfanzelt**	Felix 206	120kW	
Spinelli, 2015b		**Welte**	130T	113kW	
Spinelli, 2015b		**HSM**	208F	129kW	
Spinelli, 2015b		**Pfannzelt**	Felix 206	130kW	
Suvinen, 2006		**Timberjack**	1110	114kW	
Suvinen, 2006		**Timberjack**	1110	114kW	
Vangansbeke, 2015		**John Deere**	1010E		
Walsh, 2014		**Timbco**	820D	338 hp(?)	8w
Yoshioka, 2000		**Oikawa Motors**	RMF-CH		
Yoshioka, 2005		**Oikawa Motors**	RM8WDB-6HG		
Zhang, 2015					

		Consumption		**Emission**	**Site spec**	**Wood spec**
Author, year	**Productivity**	**Fuel**	**Lubrificants**	**CO2**	**Slope**	
Abbas, 2014		12,11l/PMH				CC/SW/SC
Ackermann, 2016	4,18/3,24PMH-7,37/11,40m3/PMH	12l/PMH	10% of fuel cost			TH
Ackermann, 2017	45,92m3/PMH	13,45L/SMH	1,09l/SMH	36,08kg/SMH	Minimal	CC
Ackermann, 2017	45,92m3/PMH	13,45L/SMH	1,09l/SMH	36,08kg/SMH	Minimal	CC
Alam, 2011	15,90m3/PMH	8,50l/PMH		For HS		CC
Alam, 2011	11,80m3/PMH	8,50l/PMH		For HS		TH
Apafalan, 2017	19,16 m3ob/PMH	11,14l/PMH			10%	CC-CTL
Asikainen, 2011		52E/PMH				
Asikainen, 2011		40E/PMH				
Asikainen, 2011		74E/PMH				
Athanassidis, 2000		935l/1000m3	17l/1000m3			
Berg, 2012	For HS	For HS		For HS		

Boku task, 2019						
Brinker, 2002		5,88$/PMH	2,16$/PMH			
Brinker, 2002		4,18	1,54			
Brinker, 2002		5,48	2,02			
Brinker, 2002		4,4	1,62			
Brinker, 2002		5,74	2,11			
Brinker, 2002		7,58	2,79			
Brinker, 2002		4,51	1,66			
Brinker, 2002		4,51	1,66			
Brinker, 2002		6,67	2,45			
Brinker, 2002		6,67	2,45			
Brinker, 2002		9,38	3,45			
Brinker, 2002		3,97	1,46			
Brinker, 2002		6,06	2,23			
Brinker, 2002		7,58	2,79			
Cremer, 2017	23,7m3loose/PMH	10l/PMH			2%	Sawlogs, pulpwood
Cremer, 2017	23,7m3loose/PMH	10l/PMH			5%	Sawlogs, pulpwood
De La Fuente, 2016		12,4l/PMH		For HS		Sawlogs, pulpwood
De La Fuente, 2016		14,2l/PMH		For HS		Sawlogs, pulpwood
Dembure, 2019		17l/PMH	20% fuel		Flat-gentle	CTL
Dias, 2007		12l/PMH		2431gCO2/m3		
Enache, 2015		13,9l/PMH		36,3kg/PMH		CTL/TH
Engel, 2012		7,5l/PMH	0,15+0,3l/PMH			
England, 2013						S/PMH

Engler, 2016		9,33E/PMH	0,93E/l		15-42%	CC
Engler, 2016		9,66E/PMH	0,93E/PMH		15-42%	CC
Eriksson, 2006		81MJ/t				TH
Eriksson, 2006		61MJ/t				CC
Ghaffariyan, 2015	86m3/PMH	16,4l/PMH			Flat	CC
Ghaffariyan, 2015	71m3/PMH	16,9l/PMH			Flat	CC
Gonzalez-Garcia, 2013	32m3/PMHa	12,78kg/PMH	2,1kg/PMHayear	For HS		TH
Gonzalez-Garcia, 2013	60	13,91	2,9	For HS		TH
Gonzalez-Garcia, 2013	74	16,33	3,5	For HS		TH
Gonzalez-Garcia, 2013	71	16,3	3,6	For HS		TH
Gonzalez-Garcia, 2013	30	12,96	1	For HS		TH
Gonzalez-Garcia, 2013	24	12,85	0,8	For HS		TH
Gonzalez-Garcia, 2013	55	12,8	1,9	For HS		TH
Gonzalez-Garcia, 2013	51	12,76	1	For HS		TH
Gonzalez-Garcia, 2013	86	14,02	3	For HS		TH
Gonzalez-Garcia, 2013	51	12,76	1	For HS		TH
Gonzalez-Garcia, 2013	168	11,6	3,9	For HS		TH
Gonzalez-Garcia, 2013	569	11,76	13,3	For HS		CC

Gonzalez-Garcia, 2014		10,3	1	For HS		TH
Gonzalez-Garcia, 2014		11,9	2,3	For HS		TH
Gonzalez-Garcia, 2014		9,58	5,5	For HS		CC
Gonzalez-Garcia, 2014		9,64	6,3	For HS		CC
Gonzalez-Garcia, 2014		11,09	1,9	For HS		TH
Gonzalez-Garcia, 2014		10,55	1,7	For HS		TH
Gustavsson, 2011		9,5l/PMH				
Handler, 2014		12,1+-7,2				CC/SW/SC
Holzleitner, 2010		11,1l/PMH				
Holzleitner, 2010		11,1l/PMH				
Holzleitner, 2010		11,1l/PMH				
Holzleitner, 2010		11,1l/PMH				
Holzleitner, 2010		11,1l/PMH				
Holzleitner, 2010		11,1l/PMH				
Holzleitner, 2010		11,1l/PMH				
Holzleitner, 2010		11,1l/PMH				
Kaleja, 2018	4,7m3/PMH	4.93 ± 0.26 l/PMHr				
Kaleja, 2018	4,7m3/PMH	4.93 ± 0.26 l/PMHr				
Kaleja, 2018b	10,0m3/PMH	12l/PMH	18g/PMH			
Kaleja, 2018b	37,5m3biomass/PMH	12l/PMH	15g/PMH			
Karha, 2018	13,5m3/PMH/23,5m3/PMH	12dm3/PMH				TH/CC
Karha, 2018	13,5m3/PMH/23,5m3/PMH	12dm3/PMH				TH/CC

Karha, 2018	13,5m3/PMH/23,5m3/PMH	12dm3/PMH				TH/CC
Kenney, 2014		2,93gal/PMH				
Kilpelainen, 2011	11,80m3/PMH	8,5l/PMH			<10%	TH
Kilpelainen, 2011	15,90m3/PMH	8,5l/PMH			<10%	CC
Klein, 2016	13-7m3/PMH	8,5l/PMH				TH - (SW/IW)
Klein, 2016	16,5-7,1m3/PMH	8,5l/PMH				CC - (SW/IW)
Klvac, 2010	9,47m3/PMH	1364l/1000m3	37,9;/1000m3			Ire
Klvac, 2010	9,88m3/PMH	1155l/1000m3	17,1l/1000m3			Ire
Klvac, 2010	8,02m3/PMH	750l/1000m3	17l/1000m3			Ire
Klvac, 2010	15,8m3/PMH	1220l/1000m3	27l/1000m3			Swe
Klvac, 2010	15,8m3/PMH	902l/1000m3	16l/1000m3			Swe
Klvac, 2010	15,8m3/PMH	878l/1000m3	15l/1000m3			Swe
Klvac, 2009	9,33m3/PMH	1155l/1000m3				CC
Klvac, 2009	9,33m3/PMH	1155l/1000m3				CC
Klvac, 2009	9,33m3/PMH	1155l/1000m3				CC
Klvac, 2009	9,33m3/PMH	1155l/1000m3				CC
Laitila, 2010		28594,44l/year				WT
Lindroos, 2014		16,0l/PMH				
Lindroos, 2014		16,0l/PMH				
Lindroos, 2014		14,2l/PMH				
Lindroos, 2014		14,2l/PMH				
Lindroos, 2014		14,9l/PMH				
Markewitz, 2006		12-15l/PMH				
Markewitz, 2006		12l/PMH				
Markewitz, 2006		34+3l/PMH				
Mederski, 2013	4,33m3/PMH	1,15l/PMH				
Mederski, 2013	9,09m3/PMH	7,89l/PMH				
Nordfjell, 2003	28,65m3/PMH	9,4l/PMH			1-2 class	

Nordfjell, 2003	21,5m3/PMH	9,85l/PMH			1-2 class	
Nordfjell, 2003	25,5m3/PMH	12,7l/PMH			1-2 class	
Nordfjell, 2003	23,3m3/PMH	14,2l/PMH			1-2 class	
Nordfjell, 2003	21,6m3/PMH	12,9l/PMH			1-2 class	
Nordfjell, 2003	12,5m3/PMH	10,3l/PMH			1-2 class	
Nordfjell, 2003	10,0m3/PMH	9,6l/PMH			1-2 class	
Nordfjell, 2003	11,8m3/PMH	12L,5l/PMH			1-2 class	
Nordfjell, 2003	4,65m3/PMH	1,5l/PMH			1-2 class	
Oekl, 2019		23,07l/PMH				
Oekl, 2019		32,05l/PMH				
Oekl, 2019		35,35l/PMH				
Ottar, 2006		1,03l/m3				Pulpwood
Pandur, 2018		17,36l/PMH			Flat	
Puttock, 2013	17,2m3/PMH	7l/PMH			2.3.1 G	
Rotensteiner, 2008		10l/PMH	25%			
Routa, 2012	11,80m3/PMH	8,5l/PMH				
Rozitis, 2017	16m3/PMH	14l/PMH				
Sanchez-Garcia, 2016	6,75odt/PMH	13,22E/PMH				
Sanchez-Garcia, 2016	11,76odt/PMH	20,98E/PMH				
Spinelli, 2006	8,7freshtonnes/SMH	10l/PMH			5-10%	CC-CTL
Spinelli, 2009		20l/SH				
Spinelli, 2009		10l/SH				
Spinelli, 2010	4,55m3/PMH	4,5 l/PMH	30% fuel costs		0	
Spinelli, 2010	4,55m3/PMH	4,5l/PMH	30% fuel costs		15%	
Spinelli, 2011		12,1E/PMH			40%-60%	
Spinelli, 2014b	3,15t/PMH	8.0 l/PMH				
Spinelli, 2015b	9,4m3/PMH	8,2 l/PMH				CTL
Spinelli, 2015b	8,1m3/PMH	11,47 l/PMH				CTL

Spinelli, 2015b	3,2m3/PMH	7,14 l/PMH				CTL
Suvinen, 2006		240g/kWh			5%	
Suvinen, 2006		240g/kWh			25%	
Vangansbeke, 2015		11,36l/PMH				WTH/TH
Walsh, 2014		20l/PMH	50% fuel costs		Flat	
Yoshioka, 2000		3,18 cc/s				TH
Yoshioka, 2005		0,52 cm3/s				
Zhang, 2015	For HS	For HS				SC/SW/CC

Author, year	
Abbas, 2014	
Ackermann, 2016	Pine
Ackermann, 2017	Pine
Ackermann, 2017	Pine
Alam, 2011	Scots P, Norway Spruce
Alam, 2011	Scots P, Norway Spruce
Apafalan, 2017	Norway Spruce
Asikainen, 2011	
Asikainen, 2011	
Asikainen, 2011	Pine, Sitka Spruce
Athanassidis, 2000	
Berg, 2012	
Boku task, 2019	
Brinker, 2002	
Brinker, 2002	
Brinker, 2002	

Brinker, 2002	
Brinker, 2002	
Brinker, 2002	
Brinker, 2002	
Brinker, 2002	
Brinker, 2002	
Brinker, 2002	
Brinker, 2002	
Brinker, 2002	
Brinker, 2002	
Brinker, 2002	
Cremer, 2017	Picea Abies
Cremer, 2017	Picea Abies
De La Fuente, 2016	Scots Pine
De La Fuente, 2016	Scots Pine
Dembure, 2019	Pinus Eliotii
Dias, 2007	Eucalypt, Maritime P.
Enache, 2015	
Engel, 2012	Spruce
England, 2013	
Engler, 2016	Eucaliptus spp
Engler, 2016	Mytilaria spp
Eriksson, 2006	Norway Spruce
Eriksson, 2006	Norway Spruce
Ghaffariyan, 2015	Pinus Radiata
Ghaffariyan, 2015	Pinus Radiata
Gonzalez-Garcia, 2013	Douglas Fir

Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2013	Douglas Fir
Gonzalez-Garcia, 2014	Pinus Pinaster
Gonzalez-Garcia, 2014	Pinus Pinaster
Gonzalez-Garcia, 2014	Pinus Pinaster
Gonzalez-Garcia, 2014	Pinus Pinaster
Gonzalez-Garcia, 2014	Pinus Pinaster

Gonzalez-Garcia, 2014	Pinus Pinaster
Gustavsson, 2011	
Handler, 2014	
Holzleitner, 2010	
Holzleitner, 2010	
Holzleitner, 2010	
Holzleitner, 2010	
Holzleitner, 2010	
Holzleitner, 2010	
Holzleitner, 2010	
Holzleitner, 2010	
Kaleja, 2018	Spruce
Kaleja, 2018	Birch
Kaleja, 2018b	
Kaleja, 2018b	
Karha, 2018	Spruce, birch, scots pine
Karha, 2018	Spruce, birch, scots pine
Karha, 2018	Spruce, birch, scots pine
Kenney, 2014	
Kilpelainen, 2011	
Kilpelainen, 2011	
Klein, 2016	Beech, Oak, Spruce, Pine
Klein, 2016	Beech, Oak, Spruce, Pine
Klvac, 2010	
Klvac, 2010	
Klvac, 2010	
Klvac, 2010	

Klvac, 2010	
Klvac, 2010	
Klvac, 2009	
Klvac, 2009	
Klvac, 2009	
Klvac, 2009	
Laitila, 2010	Pine
Lindroos, 2014	
Lindroos, 2014	
Lindroos, 2014	
Lindroos, 2014	
Lindroos, 2014	
Markewitz, 2006	
Markewitz, 2006	
Markewitz, 2006	
Mederski, 2013	
Mederski, 2013	
Nordfjell, 2003	Scots Pine
Nordfjell, 2003	Scots Pine
Nordfjell, 2003	Scots Pine
Nordfjell, 2003	Scots Pine
Nordfjell, 2003	Scots Pine
Nordfjell, 2003	Scots Pine
Nordfjell, 2003	Scots Pine
Nordfjell, 2003	Scots Pine
Nordfjell, 2003	Scots Pine
Oekl, 2019	
Oekl, 2019	

Oekl, 2019	
Ottar, 2006	
Pandur, 2018	Pedunculate oak
Puttock, 2013	Aspen, ash, birch
Rotensteiner, 2008	
Routa, 2012	
Rozitis, 2017	Spruce and birch
Sanchez-Garcia, 2016	Eucalypt
Sanchez-Garcia, 2016	Eucalypt
Spinelli, 2006	Eucalypt
Spinelli, 2009	
Spinelli, 2009	
Spinelli, 2010	Walnut, ash, alder
Spinelli, 2010	Pine
Spinelli, 2011	
Spinelli, 2014b	
Spinelli, 2015b	
Spinelli, 2015b	
Spinelli, 2015b	
Suvinen, 2006	
Suvinen, 2006	
Vangansbeke, 2015	Scot Pine
Walsh, 2014	Pinus Radiata
Yoshioka, 2000	Cryptomeria Japonica
Yoshioka, 2005	Japanes cedar
Zhang, 2015	

8.2.6 Harvester

		Machine spec					
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Head**	**Productivity**
Abbas, 2014					h		For HS
Abbas, 2014					fb		For HS
Abbas, 2014					fd		For HS
Abbas, 2014					h		For HS
Abbas, 2018					fb		For HS
Ackermann, 2016		**Tigercat**	H822c		h		2,14/4,15PMH-17,13/7m3/PMH
Ackermann, 2017		**John Deere**	759JH	179,7kW	h		54,13m3/PMH
Alam, 2011							8,20m3/PMH
Alam, 2011							17,20m3/PMH
Apafalan, 2017		**Valmet**	911,4	170kW	h		26,47 m3ob/PMH
Asakinen, 2011					fb		
Asakinen, 2011					h		
Athanassiadis, 2000					Single grip		
Athanassiadis, 2000					Double grip		
Berg, 2003							7,25m3/PMH
Berg, 2003							15,5m3/PMH
Berg, 2012							For HS
Blouin, 2013					fb		35,3m3/PMH

Blouin, 2013							64,9m3/PMH
Boku task, 2019		Silvatec	886TH				6,86m3/PMH
Brinker, 2002		Barko	685	140hp	fb		
Brinker, 2002		Barko	785	174	fb		
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Head**	**Productivity**
Brinker, 2002		Barko	885	215	fb		
Brinker, 2002		Franklin-TF	C3600 HTFB	152	fb		
Brinker, 2002		Franklin-TF	C4500 HTFB	152	fb		
Brinker, 2002		Franklin-TF	C4800 HTFB	174	fb		
Brinker, 2002		Franklin-TF	C5000 HTFB	174	fb		
Brinker, 2002		Franklin-TF	C5500 HTFB	210	fb		
Brinker, 2002		John Deere	643G	170	fb		
Brinker, 2002		John Deere	843G	200	fb		
Brinker, 2002		Tigercat	720B	165	fb		
Brinker, 2002		Tigercat	720C	174	fb		
Brinker, 2002		Tigercat	726B	215	fb		
Brinker, 2002		Timbco	TB820-D	260	fb		
Brinker, 2002		Timbco	TB820-D	260	fb		
Brinker, 2002		Tigercat	845B	205	fb		
Brinker, 2002		Tigercat	845B	205	fb		
Brinker, 2002		Tigercat	H845B	230	fb		
Brinker, 2002		Tigercat	860	250	fb		
Brinker, 2002		Timbco	T415-D	200	fb		
Brinker, 2002		Timbco	T425-D	215	fb		
Brinker, 2002		Timbco	T445-D	260	fb		
Brinker, 2002		Timbco	T450-D	260	fb		
Brinker, 2002		Timbco	T455-D	260	fb		

Author, year	Pub. Type	Maker	Model	Power	Type	Head	Productivity
Brinker, 2002		Timberjack	608L	230	fb		
Brinker, 2002		Timberjack	950	230	fb		
Brinker, 2002		Cat	550	163	h		
Brinker, 2002		Cat	570	221	h		
Brinker, 2002		Ponsse	HS10	210	h		
Brinker, 2002		Ponsse	HS16	210	h		
Brinker, 2002		Rottne	2004	120	h		
Brinker, 2002		Rottne	5000	170	h		
Brinker, 2002		Rottne	SMV/RAPID EGS	185	h		
Brinker, 2002		Rottne	SMV/RAPID TGS	170	h		
Brinker, 2002		Timberjack	1270B	204	h		
Danilovic, 2011		John Deere	1470D ECO III				
Dembure, 2019		Tigercat	830C	245kW			
Di Fulvio, 2017				220kW	h		
Di Fulvio, 2017				119kW	h		
Di Fulvio, 2017				212kW	fb		
Di Fulvio, 2017		Komatsu	931.1	185kW	h		
Di Fulvio, 2017		John Deere	1270D	160kW	h		
Di Fulvio, 2017		John Deere	1270-1470	170kW	h		
Di Fulvio, 2017				100kW	h		
Di Fulvio, 2017		John Deere	1070	136kW	h		
Di Fulvio, 2017				160kW	h		
Di Fulvio, 2017		John Deere	1270D	160kW	h		
Di Fulvio, 2017		TimberPro	TL725B	225kW	h		
Di Fulvio, 2017				160kW	h		
Di Fulvio, 2017		John Deere	1470	145kW	h		

Di Fulvio, 2017				160kW	h		
Di Fulvio, 2017				220kW	h		
Di Fulvio, 2017				212kW	fb		
Di Fulvio, 2017				179kW	fb		
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Head**	**Productivity**
Di Fulvio, 2017				149kW	h		
Di Fulvio, 2017		Timbco	425	129kW	fb		
Di Fulvio, 2017		Fabtek	153	123kW	fb		
Di Fulvio, 2017		Valmet		97kW	fb		
Di Fulvio, 2017				220kW	fb		
Di Fulvio, 2017		John Deere	643K	130kW	fb		
Di Fulvio, 2017		Cat	563C	152kW	fb		
Di Fulvio, 2017		John Deere	1170E	145kW	h		
Dias, 2007							
Dodson, 2015		John Deere	759J	241hp	h		
Dodson, 2015		Cat	511	247hp	h		
Dodson, 2015		Cat	521	284hp			
Dodson, 2015		Cat	522B	284hp			
Dodson, 2015		Timbco	XT445L-2	300hp	h		
Dodson, 2015		Timbco	XT430L-2	300hp	h		
Dodson, 2015		Timberpro	TL735B	300hp	h		
Dodson, 2015		Cat	541	305hp			
Dodson, 2015		Cat	552	305hp			
Dodson, 2015		Cat	551	308hp			
Dodson, 2015		Tigercat	LX830	300hp	h		
Dodson, 2015		John Deere	2454D logger	194hp	p		
Dodson, 2015		Komatsu	PC210LC-10	160HP	p		

Dodson, 2015		Pierce	Titan 22	194hp	p		
Dodson, 2015		Pierce	Titan 23	194hp	p		
Dodson, 2015		Komatsu	PC290LC-1	213hp	p		
Dodson, 2015		Pierce	GP	194hp	p		
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Head**	**Productivity**
Enache, 2015							18,8m3/PMH
Enache, 2015							1,6m3/PMH
Enache, 2015							28,8m3/PMH
Enache, 2015							30m3/PMH
Enache, 2015							18,5m3/PMH
Enache, 2015							37m3/PMH
Enache, 2015							11,3m3/PMH
Enache, 2015							13,7m3/PMH
Enache, 2015							12,0m3/PMH
Enache, 2015							6,8m3/PMH
Enache, 2015							5,2m3/PMH
Enache, 2015							5,3m3/PMH
Engel, 2012		John Deere	1070D				
Engler, 2016		**John Deere**	1270 D		h		
Engler, 2016							0,58-0,69m3/PMH
Engler, 2016		**John Deere**	1270D			H672C	0,58-0,69m3/PMH
Gasol, 2009				126kW			
Ghaffariyan, 2013b		**Tigercat**	845C	191kW	fb	Tigercat 2001	97.26 GMT/PMH0
Ghaffariyan, 2015							90-88m3/PMH
Gonzalez-Garcia, 2013				85kW			32m3/PMHa
Gonzalez-Garcia, 2013				85kW			60

Gonzalez-Garcia, 2013				85kW			74
Gonzalez-Garcia, 2013				170kW			71
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Head**	**Productivity**
Gonzalez-Garcia, 2013				85Kw			30
Gonzalez-Garcia, 2013				85Kw			24
Gonzalez-Garcia, 2013				85Kw			55
Gonzalez-Garcia, 2013				85Kw			51
Gonzalez-Garcia, 2013				85Kw			86
Gonzalez-Garcia, 2013				85Kw			51
Gonzalez-Garcia, 2013				85Kw			168
Gonzalez-Garcia, 2013				170kW			569
Gonzalez-Garcia, 2014				85kW			
Gonzalez-Garcia, 2014				85kW			
Gonzalez-Garcia, 2014				85kW			
Gonzalez-Garcia, 2014				170kW			
Gonzalez-Garcia, 2014				85kW			

Gonzalez-Garcia, 2014				85kW			
Greene, 2014					fb		23,12t/PMH
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Head**	**Productivity**
Handler, 2014					h		
Handler, 2014					fb		
Holzleitner, 2010		Timberjack	1270				
Holzleitner, 2010		Valmet	941				
Holzleitner, 2010		Valmet	911.4				
Holzleitner, 2010		Valmet	901.3				
Johnson, 2005					fb		17,28100ft3/SMH
Johnson, 2005					fb		22,03100ft3/SMH
Kaleja, 2018		**Vimek**	404 T5				6,7m3/PMH
Kaleja, 2018b		**John Deere**	1270	170kW	h		6,7m3/PMH
Kaleja, 2018b		John Deere	1270	170kW		Mouipu 300	6,7m3/PMH15h
Karha, 2013		**Nokka**	Profi	95kW	h		8,2m3/PMH
Karha, 2013		**Timberjack**	770	82kW	h		8,2m3/PMH
Karha, 2013		**Sampo-Rosenlew**	1046X	73,5kW	h		7,9m3/PMH
Karha, 2013		**Valtra Forest**	120	88kW	th		7,9m3/PMH
Karha, 2018		Ponsse	Ergo	205kW		Ponsse H73	
Karha, 2018		John Deere	1270D ECO III	160kW		JD H414	
Karha, 2018		Logset	8H GT	205kW		LS TH 75X	
Kenney, 2014					fb		
Kenney, 2014					h		
Khiza, 2016		**John Deere**	959K		h		31,4m3/PMH
Khiza, 2016		**John Deere**	2454D		p		31,4m3/PMH
Kilpelainen, 2011							8,20m3/PMH

Kilpelainen, 2011							17,20m3/PMH
Klein, 2016							
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Head**	**Productivity**
Klein, 2016							
Klvac, 2010				Class I			9,15m3/E15
Klvac, 2010				Class II			9,24m3/E15
Klvac, 2010				Class III			8,57m3/E15
Klvac, 2010				Class I			12,96m3/E15
Klvac, 2010				Class II			12,96m3/E15
Klvac, 2010				Class III			12,96m3/E15
Klvac, 2009		**Ponsse**	HS15eH60	114,1kW	h		8,74
Klvac, 2009		**Ponsse**	HS15 ERGO	156,6kW	h		8,74
Klvac, 2009		**Silvatec**	886TH/355MD40	152,1kW	h		8,74
Laitila, 2010						Timberjack 745	
Lijewski, 2013				129kW	h		
Lijewski, 2013				129kW			
Lijewski, 2017		**John Deere**	1270E	170kW	h		21,67m3/PMH
Lijewski, 2017		John Deere	1270E	170kW			21,67m3/PMH
Lovarelli, 2018				335kW			
Magagnotti, 2017		**Skogsjan**	495	165kW	h		13,3m3/PMH
Magagnotti, 2017		**Ecolog**	580	205kW	h		12,7m3/PMH
Magagnotti, 2017		**John Deere**	1470	180kW	h		21,8m3/PMH
Markewitz, 2006		**Timberjack**	1270B		h		
Markewitz, 2006		**Rottne**	EGS rapid		h		
Markewitz, 2006		**Timberjack**	2618		fb		
Markewitz, 2006		**Bell**	model T		fb		

Markewitz, 2006		**Timberjack**	840		fb		
Mederski, 2013		**Timberjack**	770		h		5,63m3/PMH
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Head**	**Productivity**
Mederski, 2013		**Timberjack**	1270B		h		10,21m3/PMH
Oekl, 2019				70kW			
Oekl, 2019				140kW			
Oekl, 2019				140kW			
Oekl, 2019				175kW			
Ottar, 2006							
Palander, 2016		John Deere					
Picchio, 2012		**John Deere**	1270C	173kW	h		
Prinz, 2018		**Ponsse**	Beaver	150kW	h		
Prinz, 2018		**Ponsse**	Scorpion King	210kW	h		
Prinz, 2018		**Ponsse**	Ergo	210kW	h		
Puttock, 2013		Rocan	Enviro	88kW		LohMax 3000	23,1m3/PMH
Schweier, 2015		**Hitachi**	Zaxis 210	122kW	ebh		
Schweier, 2015		**Hitachi**	EX135	93kW	ebh		
Schweier, 2015		**Hitachi**	EX165	73kW	ebh		
Schweier, 2015		**Cat**	317LN	81kW	ebh		
She, 2018		**Timberpro**	TL-735-B		fb		41,35odt/PMH
Spinelli, 2006				103kW	fb		
Spinelli, 2006				128kW	fb		
Spinelli, 2006				193kW	fb		
Spinelli, 2011		**John Deere**	1270				
Spinelli, 2011		**John Deere**	1110				
Spinelli, 2011							
Vangansbeke, 2015		**John Deere**	1170E		h		

Walsh, 2014		**Timbco**	475				
Yoshioka, 2005							
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Head**	**Productivity**
Zhang, 2015					fb		10,65tonnes/PMH
Zhang, 2016					p		9,86tonnes/PMH

8.2.7 Loader

		Machine spec					**Consumption**	
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Productivity**	**Fuel**	**Lubrificants**
Abbas, 2014							14,38l/PMH	
Abbas, 2018							24,1l/PMH	0,43l/PMH
Abbas, 2018							18,0l/PMH	0,32l/PMH
Becker, 2011		Serko	8000			22,6tons/PMH	34,72$/PMH	
Becker, 2011		Serco	6000			33,2tons/PMH	34,72	
Becker, 2011		Serco	7000			13,1tons/PMH	40,73	
Brinker, 2002		Barko	160D	140hp			4,40$/PMH	2,79$/PMH
Brinker, 2002		Barko	225	140			4,4	1,62
Brinker, 2002		Barko	295	166			5,21	1,62
Brinker, 2002		Franklin-TF	KBL-28	174			5,46	1,92
Brinker, 2002		Franklin-TF	KBL-35	174			5,46	2,01
Brinker, 2002		Husky	XL-175	115			3,61	2,01
Brinker, 2002		Husky	XL-175	115			3,61	1,33

Brinker, 2002		Husky	XL-275	115			3,61	1,33
Brinker, 2002		Husky	XL-275	115			3,61	1,33
Brinker, 2002		Husky	XL-375	152			4,77	1,33
Brinker, 2002		Husky	XL-375	152			4,77	1,76
Brinker, 2002		Tigercat	230B	174			5,46	1,76
Brinker, 2002		Tigercat	240B	174			5,46	2,01
Brinker, 2002		Tigercat	T240B	174			5,46	2,01
Brinker, 2002		Tigercat	T245B	174			5,46	2,01
Brinker, 2002		Tigercat	T248	174			5,46	2,01
Brinker, 2002		Timberjack	230	148			4,65	1,71
Brinker, 2002		Timberjack	330	148			4,65	1,71
Brinker, 2002		Timberjack	430	148			4,65	1,71
Brinker, 2002		Timberjack	530	240			7,54	2,77
Dembure, 2019		Hin-tech		57kW	3w		6l/PMH	15%of fuel cost
Dodson, 2015		John Deere	2154D logger	159hp			19,12$/PMH	
Dodson, 2015		Doosan	DX225 LL	155hp			19,12$/PMH	
Dodson, 2015		Komatsu	PC210LC-10	160hp			19,12$/PMH	
Dodson, 2015		Cat	320D FM	157hp			19,12$/PMH	
Dodson, 2015		Cat	325D FM	204hp			19,12$/PMH	
Dodson, 2015		Cat	330D FM	268hp			19,12$/PMH	
Dodson, 2015		Cat	324D	188hp			19,12$/PMH	
Ghaffariyan, 2013		Hitachi	ZAXIS 250L				25.1 l/PMH	
Greene, 2014						24,85ton/PMH	4,05gal/PMH	
Kenney, 2014							6,95gal/l	
Khiza, 2016		John Deere	2954D				23l/PMH	
Khiza, 2016		Caterpillar	568				30l/PMH	

Maesano, 2013		Caterpillar	966H	211kW			60,82MJ/m3	
Manzone, 2018		New Holland	WB170B	146kW			16,9l/PMH-16,8l/PMH	
Manzone, 2018		New Holland	WB170B	146kW			17,3l/PMH-17,2l/PMH	
Manzone, 2018		Euromec	EH220	125kW			11,8l/PMH-11,9l/PMH	
Manzone, 2018		Merlo	P36plus	75kW			9,4l/PMH-9,7l/PMH	
Pergola, 2018		Same	EXP80 CHD		w		4,82kg/PMH	
Picchio, 2012		Op macchine	T80	132kW	w		13l/PMH	
She, 2018						28,40-40,98odt/PMH*	14,2l/PMH-1,4l/PMH**	
She, 2018		Barko	495ML			29,43-40,17odt/PMH	14,2l/PMH-1,4l/PMH	3,064/PMH-0,31$/PMH
Spinelli, 2006				119kW	w	37,5odt/PMH	20l/SH	
Yoshida, 2014							5l/PMH	

	Emission	**Site spec**	**Wood spec**	
Author, year	**CO2**	**Slope**		
Abbas, 2014			CC/SW/SC	
Abbas, 2018			H+S	
Abbas, 2018			H+S	
Becker, 2011				
Becker, 2011				
Becker, 2011				
Brinker, 2002				
Brinker, 2002				

Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Dembure, 2019		0-12%/12-20%	TL/CTL	Pinus eliotii
Dodson, 2015				
Dodson, 2015				
Dodson, 2015				
Dodson, 2015				
Dodson, 2015				
Dodson, 2015				
Dodson, 2015				
Ghaffariyan, 2013		flat		Radiata Pine

Greene, 2014				
Kenney, 2014				
Khiza, 2016		111%		Fir, Sequoia, Hemlock
Khiza, 2016		111%		Fir, Sequoia, Hemlock
Maesano, 2013				
Manzone, 2018	117,6kg/PMH-118,4kg/PMH			
Manzone, 2018	116,2kg/PMH-116,6kg/PMH			
Manzone, 2018	107,7kg/PMH-106,8kg/PMH			
Manzone, 2018	58,1kg/PMH-58,6kg/PMH			
Pergola, 2018				
Picchio, 2012		flat	Coppice	Eucaliptus
She, 2018				Lodgepole pine
She, 2018				Lodgepole pine
Spinelli, 2006		5-10%	CC-CTL	Eucalypt
Yoshida, 2014				

8.2.8 Skidder

		Machine spec					**Consumption**	
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Productivity**	**Fuel**	**Lubrificants**

Abbas, 2014							19,31l/PMH	
Abbas, 2014							9,08l/PMH	
Abbas, 2014					gs		19,31l/PMH	
Abbas, 2014					cs		9,08l/PMH	
Abbas, 2018							37,4l/PMH	0,67l/PMH
Abbas, 2018							29,9l/PMH	0,54l/PMH
Abbas, 2018							37,4l/PMH	0,67l/PMH
Abbas, 2018							29,9l/PMH	0,54l/PMH
Becker, 2011		John Deere	440B		cs	7,2tons/PMH	21,75$/PMH	
Becker, 2011		Timberjack	380B		gs	9,6tond/PMH	22,53	
Becker, 2011		John Deere	540		cs	11,6tons/PMH	20,07	
Becker, 2011		John Deere	640		cs	11,6tons/PMH	20,07	
Becker, 2011		John Deere	440		cs	10,1tons/PMH	19,6	
Berg, 2012						For HS	For HS	
Blouin, 2013						16,7m3/PMH	25l/PMH	
Bodaghi, 2018		**Timberjack**	450C	120kW	6800cm3		1,54m3/PMH	7,20USD/PMH
Brinker, 2002		Cat	515	170hp			6,21$/PMH	2,28$/PMH
Brinker, 2002		Cat	525	185			7,11	2,61
Brinker, 2002		Cat	545	170			9,14	3,36
Brinker, 2002		Franklin-TF	170S2	204			7,06	2,6
Brinker, 2002		Franklin-TF	405S2	153			6,17	2,27
Brinker, 2002		Franklin-TF	Q70	175			7,51	2,76
Brinker, 2002		Franklin-TF	Q80	225			7,51	2,76
Brinker, 2002		Franklin-TF	Q90	174			9,34	3,43
Brinker, 2002		John Deere	548G	152			4,83	1,78
Brinker, 2002		John Deere	648G	185			6,21	2,28
Brinker, 2002		John Deere	748G	185			6,86	2,52
Brinker, 2002		Ranger	F65G	230			4,71	1,73

Brinker, 2002		Ranger	H66DS	119				7,06	2,6
Brinker, 2002		Ranger	H67H	153				7,51	2,76
Brinker, 2002		Ranger	F68G	169				9,34	3,43
Brinker, 2002		Tigercat	620	116				7,06	2,6
Brinker, 2002		Tigercat	630B	174				9,74	3,58
Brinker, 2002		Tigercat	635	185				9,74	3,58
Brinker, 2002		Timberjack	360C	148				6,01	2,21
Brinker, 2002		Timberjack	360C	174				6,01	2,21
Brinker, 2002		Timberjack	460C	174				7,06	2,6
Brinker, 2002		Timberjack	460C	185				7,06	2,6
Brinker, 2002		Timberjack	560	215				7,51	2,76
Brinker, 2002		Timberjack	660C	215				8,73	3,21
Brinker, 2002		Timberjack	660C	136				8,73	3,21
Brinker, 2002		Cat	517	136				5,52	2,03
Brinker, 2002		Cat	527	166				6,74	2,48
Brinker, 2002		Cat	535C	152hp				26,28$/PMH	
Dodson, 2015		Cat	545C	219hp				26,28$/PMH	
Dodson, 2015		John Deere	848H G	200hp				26,28$/PMH	
Dodson, 2015		Tigercat	620D	220hp				26,28$/PMH	
Dodson, 2015		Cat	527DR	150hp				26,28$/PMH	
Enache, 2013		TAF	657					7,5l/PMH	
Enache, 2013			U651					10l/PMH	
Enache, 2015							7,5m3/PMH	12,5l/PMH	
Enache, 2015							12	12,5l/PMH	
Enache, 2015							4,8	12,5l/PMH	
Enache, 2015							12,7	12,5l/PMH	
Enache, 2015							4,9	12,5l/PMH	
Enache, 2015							3,2	12,5l/PMH	

Enache, 2015				50kW		5,6	12,5l/PMH	
Enache, 2015				67kW		7,7	12,5l/PMH	
Engel, 2012		Pfanzelt	PM trac 2355				7,0l/PMH	0,14+0,3l/PMH
Ghaffariyan, 2013b		**Tigercat**	630C	184kW		60.22GMT/PMH0	91,91l/PMH	
Ghaffariyan, 2013b		**Tigercat**	630D	191kW		60.22GMT/PMH0	91,91l/PMH	
Gonzalez-Garcia, 2013				150kW		72m3/PMHa	109kg/PMHayear	1,1
Gonzalez-Garcia, 2013				150kW		819	1248	12,8
Greene, 2014							5,09gal/PMH	0,14gal/PMH
Handler, 2014							5,1+-2,3l/PMH/2,4+-1,0l/PMH	
Holzleitner, 2010		Cat	515				7,3l/PMH	
Holzleitner, 2010		Clark	Ranger				7,3l/PMH	
Holzleitner, 2010		Cat	518				7,3l/PMH	
Holzleitner, 2010		Timberjack	450				7,3l/PMH	
Holzleitner, 2010		Woody	110				7,3l/PMH	
Holzleitner, 2010		Timberjack	240				7,3l/PMH	
Holzleitner, 2010		Timberjack	380				7,3l/PMH	
Holzleitner, 2010		Timberjack	450				7,3l/PMH	
Johnson, 2005					small s	3,24100ft3/SMH	0,95gal/100ft3	0,02gal/100ft3
Johnson, 2005					medium gs	4,05100ft3/PMH	1,19gal/100ft3	0,02gal/100ft3
Kenney, 2014							6,24gal/PMH	
Klepac, 2013		Timberjack	450C				5,55$/PMH	
Maesano, 2013		Cat	535C	162kW		10,187m3/PMHworker	72,80MJ/m3	
Magagnotti, 2011				72kW		4,0m3/SMH	7l/PMH	
Markewitz, 2006		John Deere					15l/PMH	

Markewitz, 2006		Timberjack					20l/PMH	
Markewitz, 2006		D6					21l/PMH	
Markewitz, 2006		Timberjack	460D				15-22l/PMH	
Markewitz, 2006		Timberjack	560D				15-22l/PMH	
Pergola, 2018		**Fiat**	980DT				15,46kg/PMH	
Proto, 2017				110kW		21,6m3/PMH	25,50kg/PMH	0,003kg/m3
Proto, 2017b				110kW		188,4m3/d	20kg/PMH	
Proto, 2018		John Deere	548H				14,95E/PMH	
Sabo, 2005		**Timberjack**	240C	75kW		16,6m3/PMH	l/PMH6	
Sabo, 2005		**Timberjack**	240C	75kW		9,9 m3/PMH	7,0l/PMH	
She, 2018							41,07odt/PMH	
Spinelli, 2006				130kW		15odt/SMH	22l/PMH	
Spinelli, 2009		**Sisu Diesel**	20	81			9l/SH	
Spinelli, 2012		**Ecotrac**	55v	40kW				1,3dm3/PMH
Spinelli, 2013				130kW	w	15,4odt/SMH	5,78$/PMH	2,14$/PMH
Vusic, 2013		**Ecotrac**	55v	44kW		3,2-5m5/PMH	1,3kg/m3	0,03kg/m3
Yu, 2017		**Turbo Forest**		37kW				8,00$/PMH
Boku Task, 2019		**Valmet**	8050			5,63m3/PMH	7,32l/PMH	

	Emission	**Site spec**	**Wood spec**	
Author, year	**CO2**	**Slope**		
Abbas, 2014			CC/SW/SC	
Abbas, 2014			CC/SW/SC	
Abbas, 2014			CC/SW/SC	
Abbas, 2014			CC/SW/SC	
Abbas, 2018				

Abbas, 2018				
Abbas, 2018			H+S	
Abbas, 2018			H+S	
Becker, 2011				
Becker, 2011				
Becker, 2011				
Becker, 2011				
Becker, 2011				
Berg, 2012	For HS			
Blouin, 2013		Even	S	
Bodaghi, 2018		25%-39%		Beech, Hornbeam - Silver fir, beech
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
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Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Brinker, 2002				
Dodson, 2015				
Dodson, 2015				
Dodson, 2015				
Dodson, 2015				
Enache, 2013	To calculate	>55%	CC	Beech
Enache, 2013		>55%	TH	Beech
Enache, 2015	33kg/PMH			
Enache, 2015	33kg/PMH			
Enache, 2015	33kg/PMH			
Enache, 2015	33kg/PMH		RF	
Enache, 2015	33kg/PMH		RF	
Enache, 2015	33kg/PMH		RF	
Enache, 2015	33kg/PMH		SL	
Enache, 2015	33kg/PMH		SL	
Engel, 2012				
Ghaffariyan, 2013b		flat		Blue gum

Ghaffariyan, 2013b		flat		Blue gum
Gonzalez-Garcia, 2013	For HS		TH	Douglas Fir
Gonzalez-Garcia, 2013	For HS		CC	Douglas Fir
Greene, 2014				
Handler, 2014			CC/SW/SC	
Holzleitner, 2010				
Holzleitner, 2010				
Holzleitner, 2010				
Holzleitner, 2010				
Holzleitner, 2010				
Holzleitner, 2010				
Holzleitner, 2010				
Holzleitner, 2010				
Johnson, 2005			Thinning	
Johnson, 2005			Clearcut	
Kenney, 2014				
Klepac, 2013		0-5%	H	Pine
Maesano, 2013				
Magagnotti, 2011				
Markewitz, 2006				
Markewitz, 2006				
Markewitz, 2006				
Markewitz, 2006				
Markewitz, 2006				
Pergola, 2018				
Proto, 2017		43%		chestnut

Proto, 2017b			WT	roundwood
Proto, 2018		19-32%	HF	Beech, chestnut, pine
Sabo, 2005		0-20%		Fir, beech
Sabo, 2005		10-25%		Fir, beech
She, 2018				Lodgepole pine
Spinelli, 2006		5-10%	CC-CTL	Eucalypt
Spinelli, 2009				
Spinelli, 2012		42%	TH	Spruce, Fir
Spinelli, 2013			TH	Eucaliptus
Vusic, 2013	(f) 7207,76 g/m3 (o) 9,02727 g/m3	0-17%		
Yu, 2017				Eucaliptus Globulosus
Boku Task, 2019				

8.2.9 Tractor

		Machine spec					**Consumption**
Author, year	**Pub. Type**	**Maker**	**Model**	**Power**	**Type**	**Productivity**	**Fuel**
Aruga, 2011						As function of extracting distance	4,3l/PMH
Berg, 2003						5,15m3/PMH	5,5l/PMH
Berg, 2003						7,725m3/PMH	5,5l/PMH
Bodaghi, 2018		**Timberjack**	450C	120kW	4w	1,54m3/PMH	7,20USD/PMH
Bodaghi, 2018		**Same**	140 virtus	95kW	4w	0,81m3/PMH	6,10USD/PMH
Dembure, 2019		New Holland	8030	90kW			7l/PMH
Dias, 2007							10l/PMH
Enache, 2015						4,1m3/PMH	7,5l/PMH

Enache, 2015						2,3m3/PMH	7,5l/PMH
Enache, 2015					c	3,6m3/PMH	7,5l/PMH
Engel, 2012		Pfanzelt	PM trac 2355				7,0l/PMH
Greene, 2014						24,38ton/PMH	6,24gal/PMH
Handler, 2014							5,1+-2,3l/PMH/2,4+-1,0l/PMH
Johnson, 2005					4w	3,24100ft3/SMH	0,95gal/100ft3
Johnson, 2005						4,05100ft3/SMH	1,19gal/100ft3
Kenney, 2014							6,24gal/PMH
Klein, 2016							7,0l/PWH
Klepac, 2013		Timberjack	450C				5,55$/PMH
Klvac, 2012						6000m3/y	1,3l/m3
Laschi, 2016				85kW		7,95st.m3/PMH	3,44kg/PMH
Laschi, 2016				91kW		9,6t/PMH	1,80kg/PMH
Laschi, 2016				85kW		8,5t/PMH	2,2kg/PMH
Lovarelli, 2018				90kW			1,72kg/PMHa
Maesano, 2013		Caterpillar	D7G	188kW		22,67PHS15m3/PMH	78,80MJ/m3
Magagnotti, 2011				72kW	4w	4,0m3/SMH	7l/PMH
Magagnotti, 2013		Same	Silver	100kW			8l/SMH
Markewitz, 2006		John Deere					15l/PMH
Markewitz, 2006		Timberjack					20l/PMH
Markewitz, 2006		D6					21l/PMH
Markewitz, 2006		Timberjack	460D				15-22l/PMH
Markewitz, 2006		Timberjack	560D				15-22l/PMH
Pergola, 2018		**Fiat**	980DT				15,46kg/PMH
Pergola, 2018		Same	Explorer 80CHD				
Pergola, 2018		Motransa Fiat	980DT				15,46kg/PMH

Pierobon, 2015				67kW			
Pierobon, 2015				81kW			
Proto, 2017				74kW		14,1m3/PMH	14,306kg/PMH
Proto, 2017b				75kW		118,8m3/d	13,45kg/PMH
Sabo, 2005		**Timberjack**	240C	75kW	4w	16,6-9,9 m3/PMH	6,7l/PMH-7,0l/PMH
Spinelli, 2006		Valmet	8000S			13,6tons/PMH	9l/SH
Spinelli, 2009		**Sisu Diesel**	20	81	4wd		9l/SH
Spinelli, 2010		**Valtra**	130	100kW	4w		8l/PMH
Spinelli, 2010		**Valtra**	130	100kW	4w	5,7m3/PMH	8l/PMH
Spinelli, 2011		**Landini**		80hp			6,6E/PMH
Spinelli, 2011							7,7E/PMH
Spinelli, 2012		**Fiat**	55-85	40kW	t		2,1 dm3/PMH
Spinelli, 2015b		**Lamborghini**	1060	77kW			6,45 l/PMH
Spinelli, 2015b		**Same**	110	80kW			6,66 l/PMH
Spinelli, 2015b		**Same**	130	97kW			6,33 l/PMH
Spinelli, 2015b		**Lamborghini**	1060	77kW		5,9m3/PMH	6,5l/PMH
Spinelli, 2015b		**Same**	Silver 110	80kW		7,9m3/PMH	6,7l/PMH
Spinelli, 2015b		**Same**	Silver 130	97kW		6,8m3/PMH	6,3l/PMH
Talbot, 2005				81kW		50m3/PMH	0,27l/m3
Vangansbeke, 2015		**Valtra**	8950				8,29l/PMH
Vangansbeke, 2015		**Valtra**	T191				35,66l/PMH
Vangansbeke, 2015		**Valtra**	N141				19,19l/PMH
Yu, 2017		**Turbo Forest**		37kW	4w		10,53l/PMH

		Emission	**Site spec**	**Wood spec**	

Author, year	Lubrificants	CO2	Slope		
Aruga, 2011		For HS		WT	Broadleaves
Berg, 2003		For HS		TH	Pine, Spruce
Berg, 2003		For HS		CC	Pine, Spruce
Bodaghi, 2018					
Bodaghi, 2018					
Dembure, 2019	15% fuel		0-12%/12-20%	TL/CTL	Pinus eliotii
Dias, 2007					Eucalypt and Maritime Pine
Enache, 2015		19,8kg/PMH			
Enache, 2015		19,8kg/PMH		TH	
Enache, 2015		19,8kg/PMH			
Engel, 2012	0,14+0,3l/PMH				Spruce
Greene, 2014					
Handler, 2014					
Johnson, 2005	0,02gal/100ft3				
Johnson, 2005	0,02gal/100ft3				
Kenney, 2014					
Klein, 2016		For HS		TH - (SW/IW)	Beech, Oak, Spruce, Pine
Klepac, 2013					
Klvac, 2012				CC - (SW/IW)	Beech, Oak, Spruce, Pine
Laschi, 2016				SWS/WTH	Oak spp., ash, maple
Laschi, 2016				SWS/WTH	Oak spp., ash, maple
Laschi, 2016				SWS/WTH	Oak spp., ash, maple
Lovarelli, 2018			Flat	Roundwood	Poplar
Maesano, 2013					
Magagnotti, 2011			48%		Beech
Magagnotti, 2013				Salvage	Pinus Pinaster

Markewitz, 2006					
Markewitz, 2006					
Markewitz, 2006					
Markewitz, 2006					
Markewitz, 2006					
Pergola, 2018					
Pergola, 2018					
Pergola, 2018		For HS			
Pierobon, 2015		0,11%			Beech
Pierobon, 2015		0,61%			Beech
Proto, 2017			43%		chestnut
Proto, 2017b				WT	roundwood
Sabo, 2005					
Spinelli, 2006			5-10%	CC-CTL	Eucalypt
Spinelli, 2009					
Spinelli, 2010	30% fuel cost				
Spinelli, 2010			0-15%		Walnut, ash, alder, Pine
Spinelli, 2011					
Spinelli, 2011					
Spinelli, 2012					
Spinelli, 2015b					
Spinelli, 2015b					
Spinelli, 2015b					
Spinelli, 2015b				CTL	
Spinelli, 2015b				CTL	
Spinelli, 2015b				CTL	
Talbot, 2005					

Vangansbeke, 2015					
Vangansbeke, 2015					
Vangansbeke, 2015					
Yu, 2017					