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Forest Operations Sustainability: Innovative approaches to Environmental, Social and Economic aspects, applied on case studies

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FOREST OPERATIONS SUSTAINABILITY: INNOVATIVE APPROACHES TO ENVIRONMENTAL, SOCIAL AND ECONOMIC ASPECTS, APPLIED ON CASE STUDIES

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Index

FOREWORD

This work is the result of three years of studies aimed to actively contribute in enhancing knowledge regarding sustainable forest management. Starting from the wide and complex, but also fascinating, concept of sustainability, four case studies were developed concerning different topics related to environmental, social and economic aspects. The structure of this thesis is referred to the modern style generally used worldwide for PhD thesis. In detail, the general concepts and the aims of the whole work are reported in the Introduction at the beginning of the manuscript, while specific arguments are reported as in a paper, one for each chapter, with an independent structure. Each chapter is addressed to be or has been submitted as a research article to international indexed peer-reviewed journals. A conclusion section closes the manuscript with a resume of the most important results and some ideas and suggestions for further developments. The titles of the articles, together with the names of the people who collaborate in the different case studies analysed, are reported below:

- *Environmental performance of wood pellets' production through Life Cycle Analysis*; Andrea Laschi, Enrico Marchi and Sara Gonzàlez Garcìa, under revision in 'Energy';

- *Forest operations in coppice: environmental assessment of two different logging methods*; Andrea Laschi, Enrico Marchi and Sara Gonzàlez Garcìa, in submission to 'Forest Ecology and Management';

- *Identifying causes, dynamics and consequences of work accidents in forest operations in an alpine context*; Andrea Laschi, Enrico Marchi, Cristiano Foderi, Francesco Neri, in submission to 'Accident Analysis and Prevention';
- *A methodological approach exploiting modern techniques for forest road network planning*; Andrea Laschi, Niccolò Brachetti Montorselli, Francesco Neri, Enrico Marchi, in submission to 'Croatian Journal of Forest Engineering'.

CHAPTER 1

Introduction

1. INTRODUCTION

In the last years, the concept of sustainability became fundamental in our Society (Brown et al., 1987). Several definitions and meanings were attributed to this term (Kajikawa, 2008). However, the most famous expression is the one reported in the Bruntland Report, which described sustainable development as '*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*' (WCED -World Commission on Environment and Development, 1987). During the recent history, this concept had a fundamental importance in changing perspective concerning economic development. This happened because of the easy but fundamental meaning of sustainability, which had a profound impact in Society influencing consumptions, policies and productions, encompassing in practical the entire range of human values (Ascher, 2007).

In the last years, sustainability concept has been mainly related with three pillar-topics, the economy, the environment and the Society (Kastenhofer and Rammel, 2005). Different interpretations and names were given to those three elements, as for the triple-bottom-line (People, Planet, Profit) or P3 model (People, Prosperity, Planet) (Zimmerman, 2005). In practice, taking into account the three pillars, sustainability aims to the simultaneous research of social well-being, without compromising the environmental resources, through a fair economic growth (Koehler and Hecht, 2006). Following this perspective, this approach should interest areas included in different domain-oriented research fields, identified by Kajikawa in: climate, biodiversity, agriculture, fishery, forestry, energy and resources, water, economic development, health and lifestyle (Kajikawa, 2008). However, being sustainability considered in a multitude of fields with a high number of stakeholders, it is common to find concepts utilised to achieve sustainability with a poorly defined objective and a vague idea regarding definitions and concepts (Hahn and Knoke, 2010). In fact, despite the easy meaning of the general concept, a sustainable approach implies a multitude of interactions between economic, environmental and social interests. The environmental aspects have the highest impact in public opinion, even if the economics and social-related themes are often the most important at the end of the decision processes. However, it is fundamental to consider, under a sustainable approach, that the three pillars are strictly correlated each other, and one cannot disregard the others. In relation with environmental tasks, pollution, emissions, fossil depletion and ecosystem modifications are the most studied elements for enhancing sustainable productions.

Considering the Bruntland definition, and the sustainable concept in all its meanings, one of the most important topics is the use of non-renewable resources for energy production. In fact, the use of non-renewable resources is incompatible in a sustainable perspective, considering that the consumption of a resource that cannot be maintained for the future generations directly conflicts with the main aim of sustainability. Moreover, several indirect and negative effects contribute in making the use of fossil fuels one of the most important problems in pursuing a sustainable development. In particular, the use of fossil fuels has consequences in terms of pollution, emissions to atmosphere, water and soil. These environmental aspects are directly related with the well-being of Society, both in a short term period, considering the negative effects of pollution in terms of human health, and in a mid- long-term period, taking into account the potential effects regarding climate change. Moreover, the negative consequences attributable to non-renewable resources in a cost-effectiveness analysis at global scale, should suggest a negative impact regarding also the economic sustainability of fossil fuels. In this context, in the last years, renewable resources became popular as a solution for replacing fossil fuels in energy production (Bosch et al., 2015). In particular, from the Earth day in Rio in 1992 (United Nations, 1992) the key-role of renewable energies was worldwide recognized. Considering renewable energies in relation with sustainability, it clearly appears how this kind of resource could better encompass a sustainable development, having the possibility to be replaced in a short- mid-term period by a cautious and aware management. Consequently, a rising interest is concentrating on wood as a renewable raw material that potentially fits well in a sustainable perspective (Suttles et al., 2014).

Wood is a really interesting material, during human history it has been the first energy source (Gabbrielli, 2006). It had been abandoned during the first industrial revolution but in the last 20 years wood consumption started increasing again, both as biofuel and raw material. In 1999 the world wood consumption, for both roundwood and biofuels, was about $3300 \cdot 10^6$ m^3 (Parikka, 2004), increased to $3427 \cdot 10^6$ m^3 in 2005 (FAO, 2009) and it is still growing (Guo et al., 2015). For this reasons, the complexity of a sustainable management is particularly evident in forest sector, considering the wide set of different interests from different fields that characterize forest areas all over the world (De Meo et al., 2011; Sacchelli et al., 2014). In fact, in addition to the fundamental role of wood production, forests provide several functions and services to Society, which have to be guaranteed and preserved. In this context, a sustainable forest management has a fundamental role in emphasizing and preserving all forest functions (Hahn and Knoke, 2010). In particular sustainable forest management must provide to balancing yield and growth in the long term, preserve biodiversity, allow recreational activities and promote cultural values (Hasle et al., 2000); these services have to be integrated and considered balancing the economic, the social and environmental aspects. In Europe it is expected a rapid increment in wood demand, increasing by 10 to 300 millions m^3 in the period 2010-2030 (Sikkema and Fiorese, 2014), attributable in part to the new policies in terms of renewable energies; in fact, the new Renewable Energy Directive (RED) 2009/28/EC assigned to Europe the objective of reaching the 20% of energy production from renewable resources by 2020. The 42% of this quote is expected to derive from woody biomasses (EU, 2009). The growing interest in forests has a positive effect in terms of public opinion, forest management and wood production, but expose the environment to potential risks in terms of excessive utilization of the resource, which compromise the sustainable perspective.

The aim of this work was to analyse some of the most important and actual research topics on forest operations related to sustainable forest management. In particular, three different aspects were deeply investigated in order to represent the environmental, the economic and the social needs, which characterize the main interests according to sustainable approach in forest sector. As largely explained in this section, several interests from different stakeholders characterize forest sector, and sometimes these interests are not entirely compatible. The researchers must know and have to consider these differences addressing their studies. Three different topics were investigated in this thesis by analyzing representative case studies. Each case study was managed in order to provide innovative approach and/or original results and knowledge in a field related to one of the main topics previously described.

In detail, a brief summary regarding the deepened topics is reported below:

- **ENVIRONMENT** - Environmental profile of wood harvesting and wood products: the use of renewable resources is fundamental for environmental impacts reduction related to the use of fossil fuels. Nevertheless, also the production and the use of renewable resources should involve several environmental impacts. Regarding wood, many productive processes use heavy machines powered by non-renewable energies and related emissions have to be quantified. Moreover, several impacts, mainly to soil and to vegetation, could concern forest operations. For these reasons, it is necessary to quantify the potential environmental impacts related with a product, a process or a service, and Life Cycle Assessment (LCA) is one of the best method to quantify these impacts. In this work two different case studies were analysed. The first approached the wood pellets' production in a sawmill that recovers wood waste obtained from the main production, while in the second study a comparison between the environmental profile of two harvesting systems in coppice forest was developed;

- **SOCIAL** - Health and safety for forest workers: a sustainable perspective can't disregard to supply the best safety conditions to the workers. Considering the high risks for forest workers in performing forest operations, an accident analysis was developed to collect information and to understand which are the most frequent cause of injury in forest operations, and what kind of consequences are the most dangerous;
- **ECONOMY** - Forest road network planning as a fundamental tool in forest management: forest roads are structures that strongly affect technical and economic feasibility of forest operations, but potentially could heavily influence each pillar in forest sustainability. A forest road network has an environmental impact because of the disturbance allocated to soil and terrain structure; it has a economic impact depending on the extension and the maintenance state of the roads, which strongly influence the productivities in forest operations and consequently the costs. Finally forest road network has social implications related to their recreational use. In this study a methodological approach was tested in a forest area in northern Italy, by the development of different tools on Geographic Information Systems. The aim was to analyze the state of the road network and to identify the accessibility degrees of each forest management unit Moreover a method for the assessment of forest road needs has been developed in order to optimize the forest road network, maximizing benefits and reducing costs.

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CHAPTER 2

Environmental performance of wood pellets' production through Life Cycle Analysis

ABSTRACT

Forests play a key role as the source of an essential renewable material and/or fuel: wood. The aim of this study was to evaluate the environmental impacts related to high-quality pellet production for domestic heating following the Life Cycle Assessment (LCA) methodology and considering a cradle-to-gate perspective in the Tuscany region. This is representative and interesting for Italian pellet factories and for similar factories located in Central Europe, considering the Italian contribution to the production capacity of that area. All of the activities involved, from wood extraction in no-industrial forests to packed pellet production, ready for delivery to final users, were taken into account. The environmental analysis was performed in terms of seven impact categories. The results showed how the most important environmental burdens are related to the use of electricity during pellet production, being responsible for more than 90% of the total in most of the impact categories. Operations carried out in the forest produce a minor part of the impact (from 1% to less than 10% depending on the category). Four different alternative scenarios for producing and supplying electricity and heat were proposed and investigated. Substitution of the boiler by a co-generation unit showed a substantial improvement in the environmental burdens.

Keywords: environmental impact; Italy; Life Cycle Assessment; no-industrial forestry; renewable energy; domestic heating.

2.1 INTRODUCTION

Wood was the first source of energy directly used and managed by humans (Gabbrielli, 2006). In the period between the first industrial revolution and the 90s of the 20th century, the use of non-renewable energies shifted the use of wood to the background (Blondel, 2006). From the Earth Day in Rio in 1992 (United Nations, 1992), the interest in renewable energies brought wood back as a fundamental resource in a sustainable and renewable perspective. The annual storage of energy in plant material by terrestrial primary production is estimated as $2.2 \cdot 10^9$ TJ (Ashton, S. Cassidy, 2007). The global energy demand expected in 2020 is $6.6 \cdot 10^8$ TJ (EIA, 2013). Therefore, each year the energy captured by land plants (excluding croplands, wilderness, protected forests, infrastructure) is 3–4 times higher than human energy demand (Guo et al., 2015) and around 35% of that energy is estimated to be potential available energy (Haberl et al., 2013). Thus, the great potential for wood as a key resource in the global sustainability challenge is highlighted. Moreover, woody biomass is a finite resource and a correct and sustainable management plan is fundamental to preserve all the woody products and the multi-functionality of forests (Sacchelli et al., 2013a).

For that reason, to a certain extent, the forest sector has been at the vanguard in introducing the concept of sustainability over the years to familiarise the indicators for sustainable forest management (Berg et al., 2012). In fact, forests are considered as carbon sinks in the Kyoto Protocol (Unfccc, 1998), due to carbon dioxide uptake by photosynthesis (Nabuurs et al., 2008).

However, the extraction of wood as raw material for industrial applications is performed by means of operations that require several inputs and imply numerous direct and indirect emissions, such as those derived from the use of fossil fuels. Furthermore, forest operations could impact on soils, altering physical, biological and chemical properties due to the use of agrochemicals, heavy machinery and the correlated requirements of lubricants and fuels (Cambi et al., 2015).

The global demand for wood biomass is increasing. In the Renewable Energy Directive (RED) 2009/28/EC (EU, 2009), the European Union (EU) shall achieve a 20% share of renewable energy in final energy consumption across its Member States by 2020. In addition, 42% of total renewable energy is expected to be obtained from biomass, including electricity, heating and cooling [13]. For these reasons, the biomass demand is increasing in the global market and it is expected that it will continue to grow.

Several different woody products have been introduced in the last few years, pellets being the most successful one for domestic heating after firewood (ISTAT Italian National Institute of Statistics, 2014). Pellets are made by grinding wood pieces into sawdust through a hammer mill, and subsequently compressing the sawdust through 6–8 mm holes in the die of a pelletiser (Guo et al., 2015). Because of the high-pressure conditions applied, the lignin plasticises and glues the pellet when it cools. The pellets are 2–3 cm in length (Guo et al., 2015) with a moisture content in the range of 5–10% and the packing density is around 650 kg·m^{-3} (Kofman, 2007). High quality pellets, generally used in domestic heating, contain less than 0.7% and 1% of mineral ash and fine powders, respectively, and are mechanically durable (less than 2.5% are broken into finer particles after each handling) (Kofman, 2007).

Wood pellet production started in the United States as an alternative to fossil fuels during the energy crisis of the '70s (Chun Sheng et al., 2013). In the last 10 years, the demand has increased together with a demand for higher quality (Duca et al., 2014), which derived from a potential conflict between biomass used for energy and its conventional uses (e.g. wood panels) (Ackom et al., 2010; Roos et al., 1999; Schwarzbauer and Stern, 2010; Trømborg and Solberg, 2010).

The demand for pellets for domestic heating is constantly increasing and, specifically in Italy, the consumption is one of the highest in the world, with more than 1.4 Mt of pellets burned in 2013 (ISTAT Italian National Institute of Statistics, 2014). Only Sweden, Denmark, the United States and the Netherlands registered higher pellet consumption ratios including industrial use (Cocchi et al., 2011), while Italy is the most important market for both domestic pellet stoves and bagged pellets (Hiegl and Janssen, 2009). However, Italy has an insufficient production ratio in relation to its internal demand with a production capacity of about 0.8 Mt in 2010 (Cocchi et al., 2011).

Considering the increasing demand for woody biomass (Guo et al., 2015), and specifically wood pellets (Sikkema et al., 2011), as well as their key role in environmental policies as renewable energy, there is an emerging interest in quantifying the environmental impacts derived from wood pellet production. There is a rich body of scientific literature concerning environmental burdens derived from wood processing into industrial woody products such as paper pulp (González-García et al., 2009b), writing paper (Dias et al., 2007), floor coverings (Nebel et al., 2006; Petersen and Solberg, 2003), boards (González-García et al., 2009a; Rivela et al., 2007), furniture (González-García et al., 2011) or even bioethanol (González-García et al., 2010). Regarding wood pellets, some initial studies considered the transport (Magelli et al., 2009) and the use of different small-scale boilers (Monteleone et al., 2015). However, there is a lack of information about the environmental profile of pellet production. Adams et al. (Adams et al., 2015) environmentally compared pellet production with and without torrefaction following a life-cycle approach and considering industrial forests for raw material supply. There are no studies that consider the production of high-quality pellets, the most important ones for domestic stoves. Moreover, there are no studies that consider close-to-nature forest management in the wood supply chain.

Life Cycle Assessment (LCA) is an internationally recognised methodology that evaluates the entire life cycle of a product (process or activity) to identify, quantify and environmentally analyse all of the inputs and outputs involved in the production, use and disposal of a product (Baumann and Tillman, 2004). Thus, LCA is a methodology largely used not only in multiple industrial systems but also in the forest sector to improve their efficiency and to evaluate the related environmental impacts (Klein et al., 2015).

The objective of this study was to evaluate both the environmental impacts related to high-quality pellet production and the critical activities or steps throughout the production system following the LCA perspective and a cradle-to-gate approach. Special attention was paid also to forest activities to evaluate the real contribution of wood extraction to the global environmental burdens.

A representative Italian reality has been studied supported by several reasons: i) Italy is the third most important country in Europe in terms of pellet production (Sikkema et al., 2011), ii) Italy has the largest European market in bagged pellets (Hiegl and Janssen, 2009; Sikkema et al., 2011) and iii) Italian production is mainly dedicated to high-quality pellet production for domestic use [25].

Special attention has been paid in the Tuscany region (central Italy)–where the forest sector plays a key role in the economy and the territorial management–as representative for other pellet production systems distributed all over the peninsular part of Italy (VV. AA., 2009). Real primary data have been managed paying special attention to the local forest supply chain normally involved in this type of industry (Sikkema et al., 2011), to obtain reliable feedback on the significance of forest activities in bioenergy production systems.

Considering the growing interest in renewable energy, in particular in lignocellulosic biomass (EU, 2009), and the lack of studies on wood pellets, this study could be useful not only for forest sector-related industries but also for the energy sector and policymakers.

2.2 MATERIALS AND METHODS

LCA methodology permits analysis of the potential environmental impacts related to the entire life cycle of a production system (International Organization for Standardization, 2006). The International Organization for Standardization provides specific guidelines to obtain the same approach for every study in each research field when products or production processes are going to be compared. In this study, the guidelines established by ISO 14040 were applied so as to assess environmentally the production of wood pellets from a cradle-to-gate perspective, that is, from the raw material extraction to the packed pellets production at the factory gate. Further pellet-related activities such as their distribution to final users and retailers as well as their final use in boilers were excluded from the assessment.

2.2.1 Description of the case study

The product system object of this study is the productive chain of packed high-quality wood pellets performed at a regional scale in the Tuscany region. The forest sector in this region is very important because of the large forest surface (50% of the total area), where 11.6% of the total Italian forests are found ("INFC - National Inventory of Forests and Carbon sinks," 2005).

Italy is representative for pellet factories (about 70%) with an annual production lower than 5000 t per year (Hiegl and Janssen, 2009) where pellet is not the main product, but a secondary one produced in part using wood wastes from the main production line. The factory considered as a case study has been identified as representative for this reality because it produces wood-based panels as its main product; the residual woody stream is used for the production of pellets as co-product and presents an annual pellet production capacity of 5000 t.

In this factory, the wood waste produced is not sufficient to satisfy the pellet production requirements. Thus, residual wood from surrounding sawmills and other forest-based industries as well as logs from nearby forests are processed to obtain the annual pellet production capacity.

The functional unit selected as reference flow to report the environmental results was '1 kg of packed high-quality wood pellets'. However, it is important to highlight that two different types of packaging are used in this factory (and thus, two types of co-products are obtained): small low-density polyethylene (LDPE) bags (70% of total pellets produced) and large polypropylene (PP) bags (30% of total).

2.2.2 System boundaries description

The production chain under assessment was divided in two principal subsystems (**Figure 2.1**):

- **Subsystem 1 (SS1)** involving all forest operations carried out from the forest stand to the loading of wood logs onto trucks at the forest roadside and,
- **Subsystem 2 (SS2)** including all the activities involved in the factory under assessment from the transport of logs to the factory gate till the packed pellets are ready to be distributed to final users and retailers. Because processes related to the wood-panel production are independent of pellet production, they have not been considered in this study within the system boundaries.

In the production system under assessment, three different types of wood were processed into pellets:

- Industrial roundwood logs from forests (47% dry mass).
- Wood waste from internal production (20% dry mass): as was previously indicated, in the factory not only pellets are produced but also panels (laminated and particleboards) as the main products. Thus, all of the environmental burdens derived from the production of the wood waste were totally allocated to these panels (main product).
- Wood waste from sawmills located in the neighbourhood (33% dry mass): the same perspective was also considered here and all of the impacts derived from this residual stream production were allocated to the main product (panels and fibreboards).

The moisture content of wood influences the volume, density and weight of the wood transported from the forest to the factory. Moisture content varies from when wood is felled till it is used in the factory (Giordano, 1981). Moreover, moisture content also varies with the forest species managed. In this factory, Silver fir (*Abies alba* Miller), Chestnut (*Castanea sativa* Mill.) and Beech (*Fagus sylvatica* L.) are the main forest species processed. There is also limited use (occasionally and less than 10% of total roundwood processed) of Spruce (*Picea abies* Karst), Austrian pine (*Pinus nigra* J.F. Arnold), Black locust (*Robinia pseudoacacia* L.) and other pines (*Pinus spp.).* Considering that the main species used have similar technological and operational characteristics (Giordano, 1981), it was considered that the production of pellets from Silver fir (30% of total production), Chestnut (35% of total production) and Beech (35% of total production) was representative and appropriate for the entire production. For each species considered, the moisture content, volume and weight were estimated in every step of the pellet life cycle, from fresh wood in the forest to the final moisture of the pellet (5%). The main characteristics of the produced pellet (5% moisture content) are: 70% of the mass is hardwood and 30% softwood, 6.2 mm in diameter, 19 mm in length, moisture 5.13%, calorific value 16.9 MJ·kg^{-1} and packing density 676 kg·m^{-3}.

Subsystem 'Forest Operations'–SS1

The roundwood supply chain has been investigated in detail. The analysed pellet factory is located in the south of Tuscany (Central Italy) and it processes the wood logs from nearby producers, mainly located on the Apennines' forests. Industrial forests in this region are sporadic and located in flat terrains. The majority of forests are on mountainous areas, under a close-to-nature management where natural regeneration is required and the use of fertilisers and chemical products is generally prohibited (Regione Toscana, 2010). For these reasons, forest operations like tree seedling, site preparation, fertilising and herbicide treatments are not performed in this type of forest management regime. The species of interest in this study (Beech, Chestnut and Silver fir) are grown in high stands and in aged coppices. In these stands, timber is collected applying different types of silvicultural treatment: i) thinning and regeneration felling in high stands and ii) final felling or conversion of coppice into high stands. Because of its history, Italy has an ancient tradition of forest management, which has changed during the centuries depending on the specific needs and knowledge of the different periods (Gabbrielli, 2006). Beech and Chestnut forests have always been managed by means of natural regeneration (Nocentini, 2009), while the origin of the structure of Silver fir forests is mainly anthropic, so it is necessary to examine it in depth. Although they were traditionally private, nowadays these forests are mainly managed by public agencies and derive from natural regeneration (VV. AA., 2009).

Thus, taking into account that information, it has been considered that there is no forest activity carried out before harvesting due to the actual regime of natural stands regeneration. Logs are collected by forest activities according to the forest management plan in thinning and final cutting operations. In the examined areas, the most common operations–and therefore, considered within the subsystem boundaries–are i) motor–manual felling and processing (SS1.1) using a chainsaw (Montorselli et al., 2010) and ii) extraction either by tractor with winch (i.e. winching and skidding) or by cable yarder (SS1.2). The use of a tractor with winch is more common than the cable yarder in logging operations, so it has been assumed that 80% of total biomass has been extracted using tractor and winch and the remaining 20% by cable yarder.

To have a representative description of the real supply chain as well as reliable data to implement this study, data from different work-site conditions were analysed for all of the operations described on a total forest surface of 21 ha.

The average extraction distance is 450 m for tractor and 300 m for cable yarder. After the extraction, the last process carried out in the forest site (SS1) is the loading of wood logs onto trucks at the forest roadside by a tractor with grapple (SS1.3). Thus, the biomass is ready to be transported to the factory. The production of fuel requirements and derived tailpipe emissions in the different forest machines used in the forest processes together with the production (and maintenance) of the machines under assessment (chainsaw, tractor with winch, cable yarder and tractor with grapple) have also been considered in the study.

Subsystem 'Pellet Factory'–SS2

The SS2 includes the transport and chipping of both logs from forests and wood waste from surrounding industries (SS2.1 and SS2.2), and finally, the productive process of packed pellets in the pellet factory (SS2.3).

Concerning the transport (SS2.1), two types of lorries have been considered, representing the normal activities and depending on the travel distances. A EURO4 three-axle 26 t truck (payload 15 t) and a EURO4 four-axle 40 t truck and trailer (payload 25 t) (Hippoliti, 1997) are considered for average transport distances of 40 and 70 km, respectively. To collect wood in the nearest and in the most difficult areas, the 26 t truck is used (37% of total wood mass transported) instead of the 40 t trucks used for longer distances (63% of total wood transported).

Chipping operation (SS2.2) only processes wood logs from forests and wood waste from surrounding industries. It is periodically carried out in the factory by a contractor depending on the requirements. An industrial high-productivity mobile chipper is used for wood-chipping operation (Magagnotti et al., 2014; Marchi et al., 2011). Around 2% of the total wood chipped is lost as fine wood dust and directly sent to the atmosphere as air emission (Whittaker et al., 2011).

Packed pellet production-related activities are included in SS2.3 and the following operations have been taken into account: the grinding of wood chips (from SS2.2) and residual wood (particles) to obtain a suitable wood dust, the drying of the wood dust, pelletising and packaging. 70% of the total pellets produced are bagged in LDPE bags with a total weight of 15 $kg·bag^{-1}$. The remaining 30% is packed in PP bags with an average weight of 750 $kg·bag^{-1}$.

In this subsystem, the production of electricity required for grinding, pelletising and packaging steps (and for all the related processes, like material movement, monitoring and control of processes, air-conditioning) has been considered within the system boundaries and directly taken from the national grid (current situation). Heat is required in the drying step to reduce the moisture content of the wood dust from 36% (average value) to 5%. The heat requirement is obtained in the factory by means of combustion of wood chips (4% of total wood chips) in a boiler.

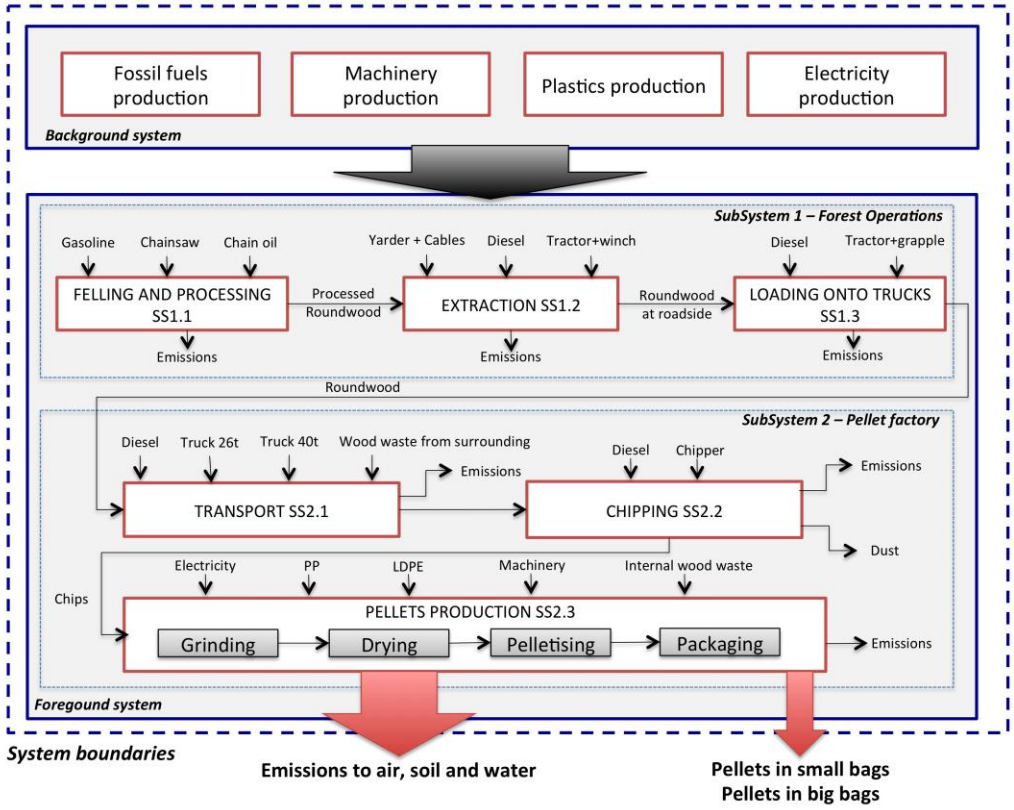

Figure 2.1. *Flowchart and system boundaries considered in the packed pellets production system under assessment*

2.2.3 Inventory data collection

In this study, primary data were managed and collected for the foreground system whenever possible by means of field data collection, surveys and questionnaires with forest workers and factory workers. Thus, only secondary data were managed for the background processes. Wood pellets are not the only product manufactured in the analysed factory. However, as explained in Section 2.1, this study considered only pellet production as an independent system; during data collection, only inputs and outputs related to pellet production were considered.

In forest operations, the primary data collected were those regarding productivities and fuel consumptions for all of the machines (chainsaw, tractor equipped with winch, cable yarder and log grapple). Secondary data managed, from specific and comparable bibliography and the ecoinvent database® (Frischknecht et al., 2004; Weidema et al., 2013), were those corresponding to tailpipe emissions from fossil fuel use (and production) in the forest machines (Prada et al., 2015; Spinelli and Magagnotti, 2014) as well as the production and use of machinery (Nemecek and Kagi, 2007; Piegai, 2000; STIHL AG & Co, 2011).

Regarding the pellet factory, inventory data collection was based on the annual production ratios in the factory under assessment. In SS2.3, it was not possible to consider separately as independent processes the grinding, drying, pelletising and packaging because the information given by the factory was aggregated for all of the operations.

The main data regarding the machines used in the different processes considered within the system boundaries are reported in **Table 2.1**. All data reported in this table correspond to primary data regarding the foreground system, such as processing hours, fuel consumption, machinery weight, machinery lifespan, repair coefficients and net productivity.

Table 2.1. *Annual productivity and consumptions as well as characteristics of machines involved in forest operations, transport and chipping activities.*

Phase	Operation	Machinery	Power (kW)	Weight (kg)	Net Productivity[a]	Fuel	Fuel consumption[a]	Operation hours	Wood processed	Lifespan	Repair coefficient	Average distance
SS1.1	Felling and Processing	Chainsaw	3.0	7	3.5 $m^3 \cdot h^{-1}$	Gasoline[d]	1.02 $kg \cdot h^{-1}$	1315	4602 m^3	2000 h[b]	0.7[b]	-
						Chain oil[c]	0.64 $kg \cdot h^{-1}$					
SS1.2	Extraction	Tractor	63	3500	5.4 $m^3 \cdot h^{-1}$	Diesel[f]	4.42 $kg \cdot h^{-1}$	685	3682 m^3	10000 h[b]	0.8 [b]	450 m
		Winch	-	300						4000 h[b]	0.75 [b]	450 m
		Cable Yarder (excl. cables)	104	5830	6.2 $m^3 \cdot h^{-1}$	Diesel[f]	5.04 $kg \cdot h^{-1}$	150	920 m^3	10000 h[b]	0.8 [b]	450 m
		Skyline and guylines	-	780						5000 h[b]	0	300 m
		Mainline	-	190						600 h[b]	0	300 m
SS1.3	Loading on Trucks	Tractor	63	3500	16.3 $m^3 \cdot h^{-1}$	Diesel[f]	2.10 $kg \cdot h^{-1}$	282	4602 m^3	10000 h[b]	0.8 [b]	-
		Grapple	-	870						4000 h[b]	0.75 [b]	-
SS2.1	Transport (payload 15t)	Truck	-	26000	82270 t·km	Diesel[f]	3.56 x 10^{-2} $kg \cdot tkm^{-1}$	-	2057 t	540000 km	-	40 km
	Transport (payload 25t)	Truck and trailer	-	40000	248169 t·km	Diesel[f]	2.17 x 10^{-2} $kg \cdot tkm^{-1}$	-	3545 t	540000 km	-	70 km
SS2.2	Chipping	Chipper	350	24000	20.2 $t \cdot h^{-1}$	Diesel[f]	33.9 $kg \cdot h^{-1}$	244	4937 t	10 y	0.8	-

[a] referred to productive machine hours without delays (PMH$_0$); [b] (Hippoliti, 1997); [c] density 0.92 kg/l (STIHL AG & Co, 2011); [d] density 0.74 kg/l (Nemecek and Kagi, 2007); [f] density 0.84 kg/l (Nemecek and Kagi, 2007).

Table 2.2 summarises the most relevant inventory data managed in SS2.3. As previously reported, secondary data were considered for the production of fuels, electricity, plastics and machines, and they were also taken from the ecoinvent database ® (Dones et al., 2007; Hischier, 2007; Nemecek and Kagi, 2007).Ecoinvent database ® processes managed in the background system, which were partially adapted with primary data, are reported in **Table 2.3**. A few evaluations were necessary regarding the choice of some secondary data. In particular, chain oils used in chainsaw operations could have very different compositions and origins. However, throughout the field data collection, workers used high-quality biodegradable chain oils (Nemecek and Kagi, 2007; STIHL AG & Co, 2011), which was considered in the study, as reported in **Table 2.3**. Regarding the production of the PP used in the packaging step, secondary data were available only for granulate PP production, and not for the textile one commonly used in the production of big bags (Hischier, 2007). For that reason, inventory data corresponding to granulate PP production has been chosen as suitable for the analysis.

Wood flow, including losses, variation of moisture and mass during the examined cycle is represented in **Figure 2.2**.

Regarding the wood burned in the furnace (SS2.3), the carbon offset was calculated considering the ratio between the molar mass of CO_2 (44 $kg \cdot kmol^{-1}$) and the molar mass of carbon (12 $kg \cdot kmol^{-1}$), multiplied by the carbon content in woody biomass ((IPCC) International Panel on Climate Change, 2006).

The furnace produces the heat requirements for the entire factory. However, the heat rate required in pellet production is 22.5% of the total factory production and only this amount was considered under assessment within the system boundaries.

Table 2.2. *Summarised inventory table for SS2.3 (pellet production factory) per functional unit (1 kg of packed pellet).*

	Quantity	Notes
Inputs from technosphere		
Wood chips	0.93 kg	From SS2.2, 36% average moisture
Internal wood waste	0.20 kg	Particles, 5% moisture
Electricity	2.03 MJ	Italian energy mix
Heat	0.42 MJ	Combustion of 0.038 kg of wood chips from SS2.2 in the furnace, efficiency 85%. Average calorific values: 13.19 MJ/kg for silver fir, 12.83 MJ/kg for Chestnut and 12.29 MJ/kg for beech
PP	4.4×10^{-4} g	Packaging material for big bags
LDPE	2.5×10^{-3} g	Packaging film for small bags
Outputs to technosphere		
Pellets in small bags	0.7 kg	Contained in LDPE bags of 15 kg capacity
Pellets in big bags	0.3 kg	Contained in PP bags of 750 kg capacity
Outputs to environment		
Carbon dioxide	370 g	Emission to air
Wood dust	19.7 g	Emission to air
Sulphur dioxide	1.15 g	Emission to air
Nitrogen oxides	1.11 g	Emission to air
Sulphate	5.40 g	Emission to water

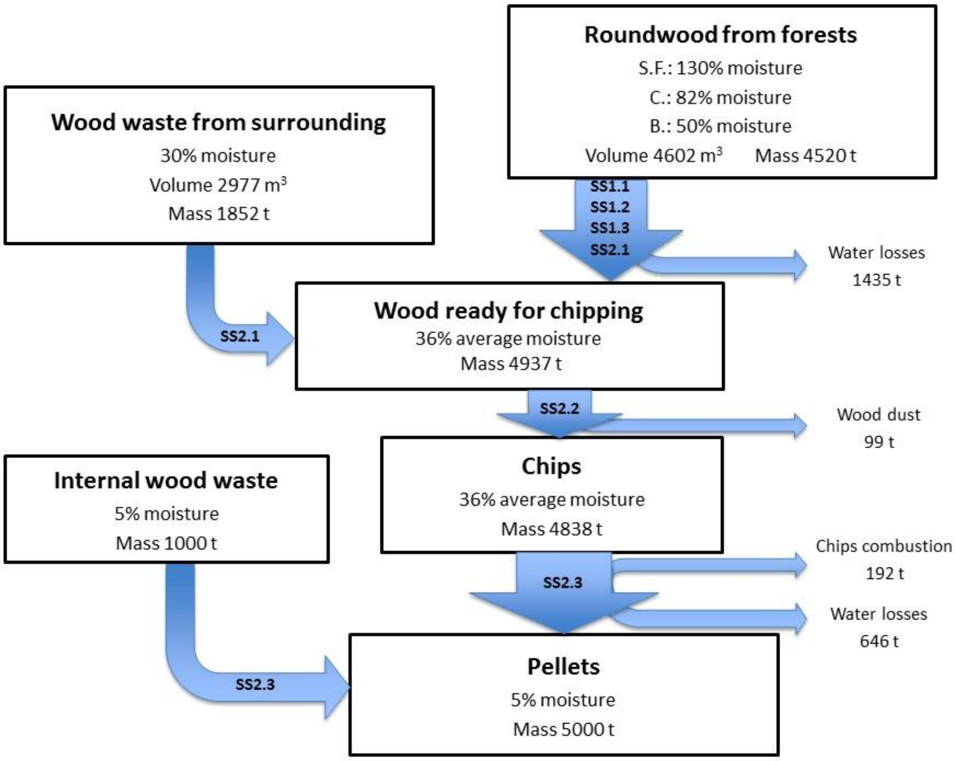

Figure 2.2. *Wood flow throughout the entire cycle. Acronyms: S.F. = Silver Fir, C. = Chestnut, B.= Beech.*

Table 2.3. *List of the main ecoinvent database ® processes considered in this study*.

8	**Input**	**Ecoinvent database ® process**
SS1.1	Chainsaw $^{\psi}$	Power saw, without catalytic converter {RER}| production | Conseq, U
SS1.1	Gasoline	Petrol, two-stroke blend {GLO}| market for | Conseq, U
SS1.1	Chain oil	Soybean oil, crude {GLO}| market for | Conseq, U
SS1.1	Chains	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Conseq, U
SS1.2	Tractor $^{\psi}$	Tractor, production/CH/I U
SS1.2	Winch $^{\psi}$	Agricultural machinery, tillage {RoW}| production | Conseq, U
SS1.2	Cable Yarder $^{\psi}$	Tractor, production/CH/I U
SS1.2	Skyline and guylines $^{\psi}$	Agricultural machinery, tillage {RoW}| production | Conseq, U
SS1.2	Mainline $^{\psi}$	Agricultural machinery, tillage {RoW}| production | Conseq, U
SS1.2	Lubricating oil	Lubricating oil {GLO}| market for | Conseq, U
SS1.2	Diesel	Diesel, at regional storage/RER U
SS1.3	Tractor $^{\psi}$	Tractor, production/CH/I U
SS1.3	Grapple $^{\psi}$	Agricultural machinery, general, production/CH/I U
SS1.3	Diesel	Diesel, at regional storage/RER U
SS2.1	Truck 15 t payload	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Conseq, U
SS2.1	Truck 25 t payload	Transport, freight, lorry >32 metric ton, EURO4 {RoW}| transport, freight, lorry >32 metric ton, EURO4 | Conseq, U
SS2.2	Chipper $^{\psi}$	Chipper, mobile, diesel {GLO}| market for | Conseq, U
SS2.2	Lubricating oil	Lubricating oil {GLO}| market for | Conseq, U
SS2.2	Knives	Steel, low-alloyed, hot rolled {GLO}| market for | Conseq, U
SS2.2	Diesel	Diesel, at regional storage/RER U
SS2.3	Wood pellet manufacture	Wood pellet manufacturing, infrastructure/RER/I U
SS2.3	Electricity	Electricity, medium voltage, production IT, at grid/IT U
SS2.3	Boiler	Furnace, wood chips, with silo, 1000kW {RoW}| production | Conseq, U
SS2.3	Plastics (PP)	Polypropylene, granulate {GLO}| market for | Conseq, U
SS2.3	Plastics (LDPE)	Packaging film, low density polyethylene {RER}| production | Conseq, U

[ψ] Process modified with primary data listed in **Table 2.1** and **Table 2.2**

2.2.4 Life Cycle Impact Assessment methodology

In this study, the environmental assessment was conducted using characterisation factors from the ReCiPe Midpoint v1.07 method (Goedkoop et al., 2013) for the following impact categories: Climate Change (CC), Ozone Depletion (OD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Photochemical Oxidant Formation (POF) and Fossil Depletion (FD). The software SimaPro 8.0.2 (PRé Consultants, n.d.) was used for the computational implementation of inventories.

2.3 RESULTS

Environmental results obtained are shown in **Table 2.4** per functional unit (1 kg of packed wood pellets) with the total characterisation results for each impact category, and the contribution percentages of the different phases are reported.

Table 2.4. *Characterisation results (per functional unit) as well as relative contributions per subsystems and processes involved in the packed pellets production system under analysis. Acronyms: Climate Change (CC), Ozone Depletion (OD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Photochemical Oxidant Formation (POF) and Fossil Depletion (FD).*

	CC	OD	TA	FE	ME	POF	FD
	kg CO_{2eq}	kg CFC-11_{eq}	kg SO_{2eq}	kg P_{eq}	kg N_{eq}	kg NMVOC	kg oil_{eq}
Total	**$4.0 \cdot 10^{-1}$**	**$3.4 \cdot 10^{-8}$**	**$1.7 \cdot 10^{-3}$**	**$7.3 \cdot 10^{-5}$**	**$6.3 \cdot 10^{-5}$**	**$1.3 \cdot 10^{-3}$**	**$1.2 \cdot 10^{-1}$**
SS1	**1.4%**	**1.7%**	**1.9%**	**1.0%**	**4.9%**	**9.5%**	**1.5%**
SS1.1 - Felling and Processing	22%	11%	10%	-2%	48%	64%	21%
SS1.2 - Extraction	65%	75%	76%	77%	44%	30%	66%
SS1.3 - Loading on trucks	13%	14%	14%	25%	8%	5%	13%
SS2	**98.6%**	**98.3%**	**98.1%**	**99.0%**	**95.1%**	**90.5%**	**98.5%**
SS2.1 - Transport	2%	2%	2%	1%	3%	5%	3%
SS2.2 - Chipping	2%	2%	3%	0%	5%	8%	2%
SS2.3 - Pellets production	96%	97%	96%	99%	92%	87%	95%

In all impact categories, processes included in SS2 covered more than 90% of the total impacts examined. The impacts related to forest operations were almost negligible in comparison with those from SS2, and were in line with the results of other related studies where environmental impacts were quantified for forest products (Parikka, 2004; Valente et al., 2011) considering the close-to-nature management analysed in this study. This type of management does not include operations like fertilising and plantation, typical in industrial forestry, which are normally the major responsibility in environmental burdens for forest activities (González-

García et al., 2012; Morales et al., 2015). In particular, SS2.3 (activities carried out within the pellet factory) was the one that mostly contributed to the environmental burdens, the production of the electricity requirement being the environmental *hotspot* because it generates the highest rate of impact in all categories (Figure 2.3). Electrical energy is necessary for all the machines and processes involved in pellet production after chipping, the grinder, sieve, pelletiser, packaging machine, conveyor belts (for material distribution) and safety dust aspirators being the most important. Moreover, in the total consumption of electricity, the monitoring and control system, lighting and air conditioning of the pellet production plant were also included.

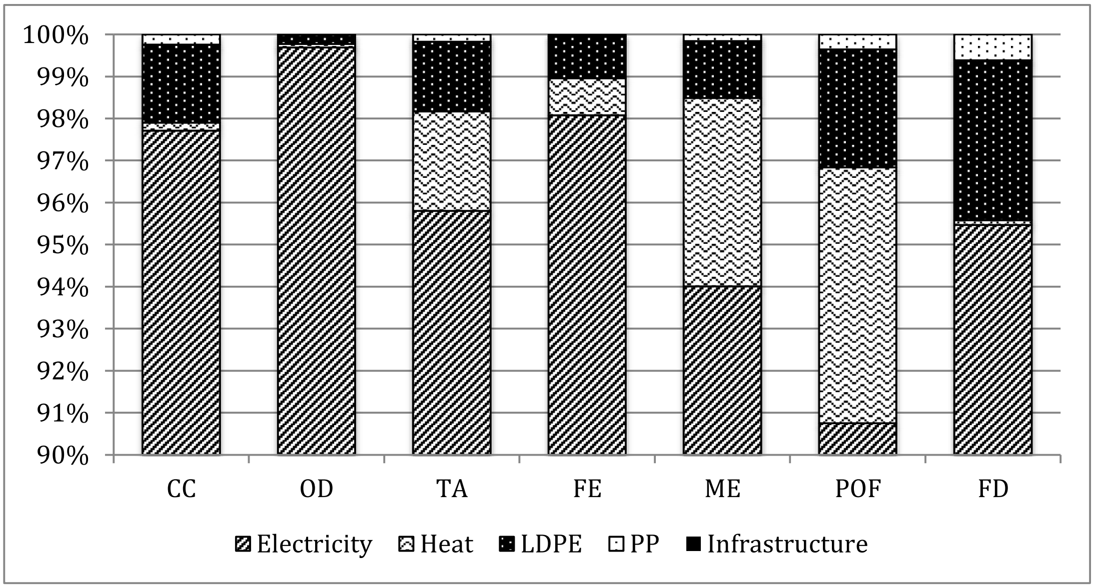

Figure 2.3. *Distribution ratios of impacts per processes involved in SS2.3, graphical representation cover 10% of total impact, the other no represented 90% of impacts is entirely covered by electricity. Acronyms: Climate Change (CC), Ozone Depletion (OD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Photochemical Oxidant Formation (POF) and Fossil Depletion (FD).*

As previously reported, the contribution from forest operations to the different environmental burdens analysed was very low compared with the factory processes (lower than 10% in all the categories). If these contributions are assessed in more detail, the highest impacts were caused by the use (and production) of diesel in forest machines being the highest consumption in the extraction phases (SS1.2). During felling and processing (SS1.1), logs stay close to the tree stump and the work is done by chainsaws. During the loading of logs onto trucks (SS1.3) the movement of logs is limited to a few metres. During the extraction (SS1.2), there is the highest request of energy in forest logging due to the transfer of logs from the felling site to the loading site with distances of hundreds of metres in difficult conditions (natural and steep terrain) using heavy machines for a huge number of operation hours.

2.3.1 Climate Change (CC)

The results showed that the production of 1 kg of packed pellets in the described situation implied an emission of 0.4 kg CO_2 eq. 94.8% of the total amount was derived from SS2.3, where the contribution of the production of electricity requirements in the involved activities was the most important (92.6% of the total emissions in all the cycles). Transport- and chipping-derived emissions covered 1.9% each of the total Greenhouse Gases (GHG) emissions while all the phases considered within the Forest Operations subsystem (SS1) involved only 1.4% of the total CO_2 eq and extraction (SS1.2) covered 65% of this value. Fossil fuels combustion emissions were the most important in SS1, covering about two thirds of the total CO_2 eq.; the highest contribution of SS1.2 was due to the use of heavy machines for a higher number of hours than SS1.3 and SS1.1 (where operations are manual). If contributing emissions are analysed in detail, 94.5% of CC is due to CO_2 emissions, 3.9% are methane emissions and the remaining 1.6% is mainly due to nitrous oxide.

2.3.2 Ozone Depletion (OD)

OD potential is reported in terms of trichlorofluoromethane equivalent emissions (kg CFC-11 eq) and the trend was similar to CC. Around 95% of contributions to this impact category were related to SS2.3, mainly due to the production of electricity requirements. The remaining contributions were almost equally distributed between the other two phases involved in SS2 (SS2.1 and SS2.2) and SS1. Regarding forest operations, the impacts were mainly derived from the extraction process (SS1.2). In this impact category, the substances that greatly influenced the results were Halon 1211 (60%), Halon 1301 (37%) and HCFC-22 (2%) derived from fossil fuels used in the involved processes.

2.3.3 Terrestrial Acidification (TA)

The potential contribution to soil acidification in the wood pellet production life-cycle (90% of total) was related to the production of electricity requirements. The remaining 10% of the acidification potential was distributed between the other processes included in SS2.3 (3.8%), the transport and chipping phases (4.3%) as well as SS1 (1.9%). Regarding the substances involved, the highest contribution was related to the sulphur dioxide emission (67.4%) followed by nitrogen oxide emission (31.4%).

2.3.4 Freshwater Eutrophication (FE)

The first impact category for aquatic eutrophication analysed was FE; the results indicate that it was the category where the SS2 had the most important role for the considered environmental burden, involving 99% of the total kg P eq emitted (electricity production reported around 96.2% of total impact). Regarding the contributing substances, phosphate emissions represented 99% of the total. The forest operations contribution was negligible.

2.3.5 Marine Eutrophication (ME)

The second impact category analysed in terms of eutrophication potential was eutrophication in marine water. The results showed that electricity production was responsible for 82% of the total N eq emissions. The chipping phase (SS2.2) contributed 4.9% and transport (SS2.1) 2.9% of total ME burdens. Forest operations had a relatively higher impact for this category than in the previous results, mainly due to the felling, processing (SS1.1) and extraction (SS1.2) phases, which contributed 2.4% and 2.2%, respectively, of N eq emissions. Different substances contributed to ME potential in terms of N eq, the most important being nitrogen oxides (60%), nitrate (27%) and nitrogen (11%).

2.3.6 Photochemical Oxidant Formation (POF)

For the potential production of Non-Methane Volatile Organic Compounds (NMVOCs) in wood pellet production, the production of electricity requirements contributed 71.6% of the total NMVOCs emissions. The remaining processes involved in SS2.3 contributed 7.3% as well as the chipping operation (SS2.2). In the forest operation subsystem (SS1), the felling and processing phase (SS1.1) contributed 6.1% of NMVOCs emission while extraction was only 2.9%. POF potential was mainly due to nitrogen oxides (73%), NMVOCs (16%) and sulphur dioxide (7%).

2.3.7 Fossil Depletion (FD)

In this category, strictly related to the use of fossil fuel, electricity production was the *hotspot*, with 89.5% of kg oil eq consumed in the wood pellet production. The other processes involved in SS2.3 covered 4.2%, transport and chipping consumed 2.5% and 2.3%, respectively, while forest operations contribution was very low (1.5% of the total). In the analysed system, natural gas was the fossil fuel with the highest depletion potential (53%) of the total, and its consumption was almost totally due to electricity production (99%). Crude oil contributed 28% of depletion potential while hard coal gave 18%.

2.4 DISCUSSION

Results displayed in the previous section clearly showed that the production of the electricity required in the activities carried out within the pellet factory (SS2.3) was the environmental *hotspot*, reporting ratios ranging from 71.6% to 96.2% with regard to the total impacts depending on the category. These remarkable contributions are mainly due to the non-renewable base of electricity consumed because it is taken directly from the Italian national grid. A large part of the Italian energy mix (78.9%) depends on fossil fuels (Dones et al., 2007), which derive negative environmental burdens. In the considered energy mix for electricity, the majority of renewable energy sources are derived from hydropower (19.9%), 0.7% from wind and only 0.5% from biomass.

The most important activities carried out within the pellet factory that require electricity are the grinding, pelletising, packaging and monitoring of all these activities. Heat is only consumed during the drying of woody material. Considering both electricity and heat used in the pellet factory, 14.5% of energy content of the final product (lower heating value of 4.69 $kWh \cdot kg^{-1}$) is spent to produce it. According to the literature, the ratio between the energy (electricity and heat) spent to produce the pellets and its energy content (considering the pellets' lower heating value) can vary between 2% and 35% (Cespi et al., 2014; Gustavsson and Karlsson, 2001;

Hellrigl, n.d.). These studies reported large differences in energy consumption because they considered different industry dimensions, efficiency of machines, wood moisture as well as different system boundaries (e.g. only pelletising, or excluding packaging (Adams et al., 2015; Cespi et al., 2014; Gustavsson and Karlsson, 2001; Hellrigl, n.d.)) in the production system under analysis. These different approaches led to different values in measuring the energy consumptions in wood pellet production (Hellrigl, n.d.). However, considering that the amount considered in this study (Table 2.2) includes all of the electricity consumption in the pellet factory, from the grinding to packaging, including all of the machines used in material movement, monitoring, controlling, air-conditioning and lighting, the energy consumption reported is consistent with this type of production (Adams et al., 2015; Cespi et al., 2014; Gustavsson and Karlsson, 2001; Hellrigl, n.d.).

Regarding the logging operations performed in the supplying forest under assessment, their derived impacts on the environmental performance estimated for the entire production system (Figure 2.1) were almost negligible (lower than 2%) in all of the impact categories except in ME and POF (4.9% and 9.5%, respectively). In the analysed case–typical in Italian forest management–the contribution of forest activities is restricted for the operations of logging. As was previously explained, there are no activities such as site preparation, planting, cleaning as well as fertilising, which are typical of industrial forest management (González-García et al., 2014a; Routa et al., 2012; Xu and Becker, 2012). The conditions of natural renovation and no-industrial productions common in the Apennines' forests allow having a very low environmental impact potential in supplying wood for industrial uses.

To evaluate how it could be possible to reduce (or not) the impact potential related to the production of electricity requirements, four different potential scenarios were proposed and compared with the current case study. Because the pellet factory works with wood, and already uses it to produce the heat requirements, the potential scenarios were built based on the use of wood as the source to produce the total or part of the energy requirements (heat and electricity) in the factory.

The differences between the case study and the scenarios in terms of quantity and quality of wood (from forests, internal waste or waste from surroundings) were only referred to the combustion, while the rates of wood used directly to produce pellets were the same as the case study in all the scenarios. The different scenarios are described below.

2.4.1 Scenario A

Considering that the factory has a wood chip boiler for heat production, this scenario was proposed considering the improvement of the infrastructure. Thus, the boiler was changed by a co-generation unit (1400 kWh) fuelled with wood and with an emissions control system (see **Table 2.5**) to produce all of the heating requirements and a part of the required electricity (Jungbluth et al., 2007). The total electrical energy produced was 10.3% of the total heat produced. This quote reduced the total consumption of electrical energy from the Italian national grid. The ratio between the residual wood (internal to the factory and collected from the nearby industries) and the wood from forest logging was the same as in the case study.

Table 2.5. *Summary of electricity, heat and wood requirements for the case study and alternative examined scenarios referred to the functional unit (1 kg of packed wood pellets). Wood quantities are referred only to energy production.*

		Case study	Scenario A	Scenario B	Scenario C	Scenario D
Electricity (MJ)	from grid	2.025	1.982	0	0	0
	from cogeneration	0	0.043α	2.025γ	2.025γ	2.025γ
Heat (MJ)	net production from furnace/cogeneration	0.42	0.42β	19.50δ	19.50δ	19.50δ
	used in the process	0.42	0.42	0.42	0.42	0.42
	wasted in environment	0	0	19.08	0	0
	sold to other industries	0	0	0	19.08	19.08
	Wood (kg)	0.04a	0.04a	1.38b	1.38b	1.60c

Ecoinvent processes ®:
α Electricity, at cogen ORC 1400kWth, wood, emission control, allocation heat
β Heat, at cogen ORC 1400kWth, wood, emission control, allocation heat
γ Electricity, at cogen 6400kWth, wood, emission control, allocation energy
δ Heat, at cogen 6400kWth, wood, emission control, allocation energy
modified with primary data for wood requirements:
a mix of wood waste and wood from forest
b wood waste
c wood from forests

2.4.2 Scenario B

In this scenario, a further change has been added as a difference to the base case study. Because the factory is located in a productive area for forest and wood sectors, there is a huge availability of wood residues. Thus, the introduction of a bigger co-generation unit (6400 kWh) than in Scenario A (see **Table 2.5**) (Jungbluth et al., 2007) was considered to produce all of the electricity requirements from wood waste collected in the surrounding areas. That residual wood must be homogenised into wood chips for better operation of the co-generation unit. Electricity production was lower than heating (electric energy produced is 10.39% of thermal energy), so the heat production exceeds the factory heat requirements and it is wasted ($9.54 \cdot 10^7$ MJ) into the environment. This is a completely theoretical scenario due to the lack of sense in producing a huge amount of heat and wasting it. However, it was useful to have a complete and gradual overview of enhancement possibilities in energy supply.

2.4.3 Scenario C

In relation to the large amount of heat wasted to the air in Scenario B, together with the position of the factory in an industrial area, Scenario C was proposed considering the possibility of supplying the extra produced heat to other industries located near the pellet factory. A system expansion perspective should be considered here because the production of these heat requirements in the corresponding industries by the conventional process should be avoided, which is based on the combustion of natural gas in an industrial furnace. Because of this procedure, the extra heat should not be lost into the atmosphere and environmental burdens should be expected to be avoided as well as the factory could ensure revenue.

2.4.4 Scenario D

This scenario was designed based on the production of the total electricity requirements by means of combustion of wood chips in a co-generation unit. However, it considered a different origin of the wood chips. As explained before, forestry is an important and developed sector in the region where the factory is placed and for that reason, it could be possible to obtain the wood to produce electricity directly from forest activities. This scenario permits comparison of the environmental burdens related to the wood chip supply, from industrial wood waste (Scenario C) and from forests (Scenario D). In comparison with Scenario C, the quantity of wood extracted from forests was not only that required for pellet production, but also included the requirement for the co-generation unit.

2.4.5 Comparison of scenarios

The four scenarios were analysed considering the same characterisation factors as those considered for assessment of the case study to obtain comparable results. Pellet production processes were assumed to be the same, with the exception of heat and electricity requirements. Regarding changes related with boiler and co-generation units, the associated production and infrastructure were taken from the ecoinvent database ® (different processes were considered, as reported in **Table 2.5**). Quantity variations in terms of fresh wood from forests and waste wood from surroundings were considered in terms of quantity, maintaining the same processes (forest operations, wood waste collection and transport) implemented in the case study. **Figure 2.4** displays the comparative environmental profiles between the potential alternative scenarios and the base case for the different impact categories under analysis.

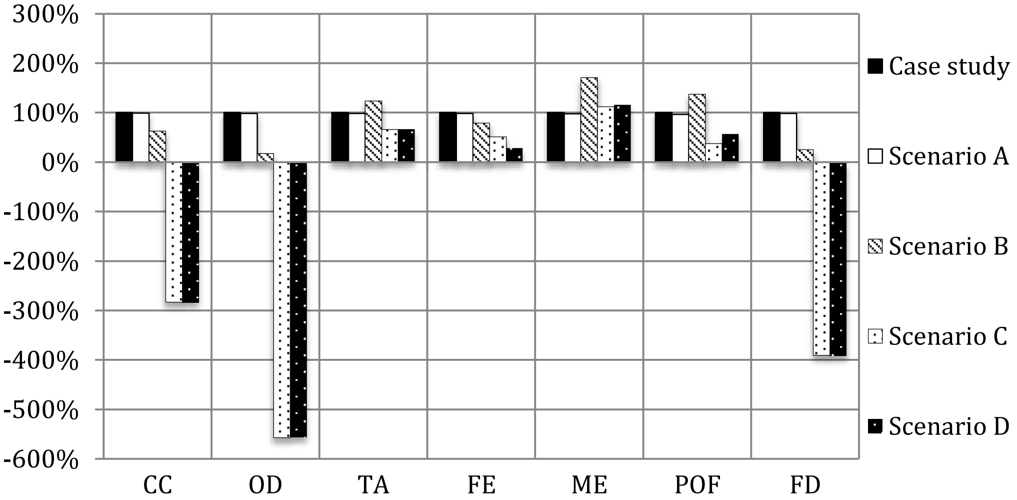

Figure 2.4. *Comparative Life Cycle Impact Assessment between the case study and the hypothetical proposed scenarios. Results are shown as the relative difference with the values obtained for the case study.*

According to these comparative results, Scenarios C and D should have the best environmental profiles with remarkable reductions in all the impact categories under assessment in comparison with the case study except in terms of ME. The use of the extra heat obtained in the co-generation unit as a product for other industrial processes avoiding thus the use of natural gas provides important environmental improvements, specifically in terms of CC (reduction of around 280% of GHG emissions regarding the case study), OD (reduction of 557%) and FD (reduction of 390%). In both scenarios, the substitution of a fossil fuel-based process by a renewable process leads to environmental credits, improving drastically the environmental profile derived from the current situation (case study). Regarding impacts derived from Scenarios C and D in terms of FE and POF, remarkable differences should be identified. Scenario C should have a better profile in POF (37% of the impact potential derived from the base case) than Scenario D (57% of the base case). In contrast, Scenario C should have a higher impact potential for FE (51%) than Scenario D (28% of the freshwater eutrophying emissions derived from the base case). These differences are due to the different origin of wood processed for energy requirements production (and involved processes). In Scenario C, the wood processed was totally residual wood collected in the surrounding industries, which was chipped in an electric industrial chipper before its combustion. In contrast, in Scenario D, the wood processed was primary wood from Apennines' forest, which was managed involving the impacts derived from its management. The wood waste derived from industrial production (Jungbluth et al., 2007) and impacts related to its production were entirely allocated to the main product, while the impacts related to the operation of collection, transport, chipping and combustion in the co-generation unit were entirely allocated to the wood pellet production.

The environmental profile derived from Scenario A slightly differed from the base case because although only the boiler was changed to a co-generation unit, only a small amount of electricity was produced (2.13% of total requirements) and the remaining electricity was taken from the Italian grid. Because of the limited efficiency in electricity production (10.3% of thermal energy produced), environmental improvements should range from 1% (for CC) to 4% (for POF) with regard to those derived from the base case.

Scenario B (extra heat produced in the co-generation unit is wasted) should show a better profile than the base case in CC (reduction of 37%), OD (83%), FE (21%) and FD (75%). This is due to the use of a renewable source for the production of all electricity requirements instead of taking electricity directly from the Italian grid, which depends considerably on fossil fuels. However, in the remaining categories, the use of a renewable resource to produce electricity (and heat) did not report environmental improvements. The environmental burdens in terms of TA, ME and POF should be increased (124%, 171% and 137%, respectively, with regard to these impacts from the base case) due to the higher quantity of wood biomass combusted and the related increase of emissions that negatively affect these impact categories.

2.5 CONCLUSION

Because of its practicality in use, the stability of the material and its easy storage (García-Maroto et al., 2014), the use of pellets is increasing in Italy, the US and northern European countries, especially for domestic heating. The use of wood pellets for heating instead of fossil fuels has a positive role in an emissions-reduction perspective. However, there are also environmental impacts derived from the pellet production process that need to be quantified. This study showed how the electricity requirements throughout the pellet production system have a key role in the environmental profile. The use of wood from forests does not have an outstanding impact on the analysed cycle. More than half of the wood material processed (dry mass) is waste material from industries and contributes to keeping low the impacts related to the wood supply chain. The use of residual wood in the production of pellets is an added value that improves the environmental profile of the final product, but also reduces the cost and increases the economic income for the producer. A reduction of the impacts related to electricity consumption could be theoretically possible by replacing the boiler with a co-generation unit. The best results could be obtained when the co-generation unit produces the total requirement of electricity and the surplus heat is distributed to other users in the neighbourhood. The analysed scenarios showed that there are no substantial differences between the use of wood waste collected from the surrounding or wood directly extracted from nearby forests. However, the case study analysed is a typical Italian situation, where the inputs in forest production are negligible and concentrated in the extraction phases. A different result could be obtained considering industrial forests where the intensive management regimes imply additional inputs, and even collecting wood from long distances. Moreover, the use of wood waste should have a minor impact on the wood market, while the use of logs for pellet production could reduce the wood availability for other production activities.

The results derived from this study are reliable and interesting not only for Italian factories but also for similar factories located in Central Europe (Bavarian region, Austria, Switzerland and France) due to the key role played by Italy in the production capacity of that area.

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CHAPTER 3

Forest operations in coppice: environmental assessment of two different logging methods

ABSTRACT

Wood is a renewable resource and it actively contributes to enhance energy production under a sustainable perspective. There are different ways for managing forests dedicated to wood production and the sustainable approach is fundamental in order to preserve the resource. In this context, Life Cycle Assessment (LCA) is an useful tool for estimating the environmental impacts related to renewable resources. Traditional coppice is a common approach for forest management in several areas, including southern Europe and, specifically, in Italy, Spain and the Balkans.

Different types of forest operations are considered for wood extraction from coppices, where the main product is firewood used in domestic heating. The aim of this work was to compare the two main common systems for firewood production (Short Wood System and Whole Tree Harvesting), in a representative environment in central Italy, by means of LCA. Seven different impact categories were evaluated in a cradle-to-gate perspective taking into account all the operations carried out from the trees felling to the firewood storage at factory.

Results showed that the extraction phase was the most important in terms of environmental burdens in firewood production and the use of heavy and high-power machines negatively influenced the emissions compared with manual operations. Finally, considering the general low-inputs involved in wood production in coppice, the transport of workers by car to the work site resulted on consistent contributions into environmental burdens. An additional analysis on soil emissions attributable to the extraction phase were made regarding Climate Change impact category, using bibliographic information. Results showed an increment of 3% and 10% of CO2eq for Whole Tree Harvesting and Short Wood System respectively.

Keywords: Life Cycle Assessment, environmental impact, no-industrial forestry, renewable energy, southern Europe.

3.1 INTRODUCTION

Forests cover almost one third of above sea level lands (Keenan et al., 2015). A multi-functional approach in forest management is applied in Europe (Sacchelli et al., 2013a) in order to guarantee constant wood production yields together with other ecosystem services such as recreational activities, environmental protection and hydro-geological protection (Saarikoski et al., 2015).

World energy demand is increasing (EIA, 2013) and a future key-role of wood in energy supply, as renewable resource, is expected (Haberl et al., 2013). Through the Renewable Energy Directive (RED) 2009/28EC (EU, 2009), European Union fixed the objective to reach the 20% of energy from renewable resources in 2020, being the 42% of total renewable energy production derived from wood. Hence, the importance of renewable energies, in particularly wood, from a perspective of emissions reduction, becomes evident. In the context of woody biomass production for energetic uses, coppices have an important role. In coppice systems the regeneration of broadleaved species consists mainly of sprouts originating from cut stumps and rotation period are shorter than high-forests (Bottalico et al., 2014). There are two main ways for coppice management: the Short Rotation Coppice (SRC) and the traditional management (Hauk et al., 2014; Spinelli et al., 2014). The first one is an industrial management focused on the maximization of the biomass yield per year (Gasol et al., 2010; Picchio et al., 2012b; Roedl, 2010), while the second is an extensive management largely used in southern Europe (Jansen and Kuiper, 2004; Spinelli et al., 2014) with longer cutting period and lower biomass annual increment than SRC. SRC follows an agricultural approach and the highest amount of biomass is obtained by means of the cultivation of fast-growing tree species performing intensive forest operations such as tillage, mechanical plantation, fertilisation and, sometimes, irrigation [12]. The tree species commonly used are *Salix spp.* and *Populus spp.* (Weih, 2004) and the rotation period is normally between 2 and 6 years. The interest related to traditional coppice in terms of sustainability is associated to the extensive management of this type of forests and to the low impacts derived from these productive forests (Picchio et al., 2009). The main product in traditional coppices is generally firewood, even though in the last decade chips production has increased, mainly due to the extraction and chipping of logging residues (branches, tree tops, and other thin material) (Sacchelli et al., 2013b). In traditional coppice the rotation period is longer than in SRC, generally ranging from 18 to 35 years. Moreover, regeneration is natural, mainly from stump resprouting, while the renovation of died stumps is guaranteed by seeds (Piussi, 1994). For these reasons, plantations are not necessary in traditional coppice. Firewood has been the most consumed woody biofuel, with a worldwide annual production in 2013 of 1.9 Mm^3, satisfying the heating and cooking requirements of the 40% of world population (Guo et al., 2015). Despite the increasing consumptions of innovative products as wood pellets and briquettes, Europe still uses more firewood than any other industrial wood product for energy (Manzone and Spinelli, 2014). Firewood is the most successful wood product for domestic heating also in Italy (ISTAT Italian National Institute of Statistics, 2014), and coppice forests under traditional management cover the 35% of the entire Italian forest surface ("INFC - National Inventory of Forests and Carbon sinks," 2005).

Extraction, transformation, use and disposal of renewable materials and fuels involve several processes with derive on environmental consequences. Related environmental impacts should have to be identified and quantified to obtain their environmental profiles and determine their environmental sustainability versus fossil ones (Sumper et al., 2011). In this context, Life Cycle Assessment (LCA) become an interesting and appropriate method to evaluate the impacts related to the production and use of renewable materials (International Organization for Standardization, 2006). Effectively LCA is an internationally recognised methodology, which identifies, quantifies and environmentally analyses all the inputs and outputs involved in the entire life cycle of a product or service, including the production, use and disposal of it. For these reasons, LCA is used not only in industrial systems, where it was born, but nowadays it is largely employed also in forest sector (Klein et al., 2015).

LCA based studies have been discussed in the forest sector for the last 20 years (Klein et al., 2015), but there is still a poor amount of reliable information based on scientific research (Heinimann, 2012). Klein et al. (Klein et al., 2015) tried to find the reason of this lack of information in the fact that, in forestry related LCA studies, the forest production is not the main objective of the study, and related information "*is only deduced from literature or calculated starting from the latest stage of the forest product chain*". However, there are some available studies which focused their attention on forest operations managing primary data in wood supply chain (González-García et al., 2014b, 2013b; Heinimann, 2012; Morales et al., 2015). Moreover, in the last years a huge number of environmental studies have been focused on forestry, especially in industrial forests (Berg and Karjalainen, 2003; Michelsen et al., 2008) and short rotation coppices (Bacenetti et al., 2016; González-García et al., 2014a, 2012; San Miguel et al., 2015). Very few studies analysed local woody supply chain, close-to-nature management (Mirabella et al., 2014; Pierobon et al., 2015) or traditional products (González-García et al., 2013a) probably attributable to the large differences in forest conditions, forest operations techniques and type of woody products at regional and national scale. The high variability in forest management, wood extraction, woody products manufacture, typical of forest sector, is well represented in Italy where forests cover more than ten million hectares (34.9% of total country surface) ("INFC - National Inventory of Forests and Carbon sinks," 2005) along north to south, and where industry of wood biomass is well developed (Scarlat et al., 2013).

Considering coppice forests under traditional management, Italy has a key role in Europe both for land occupation and firewood production

(Sacchelli et al., 2013b; Suchomel et al., 2011). The high variability of morphology and work conditions imply a huge variability of logging systems playing the slope gradient a key-role on logging systems (Di Fulvio, 2010).

The aim of this study was to investigate the environmental profile of wood biomass production considering two different harvesting systems in traditionally managed coppice forests, under typical conditions of slope and work systems. The analysis was planned in order to obtain a general overview in terms of environmental impacts related to wood biomass (mainly firewood) production. Moreover, an in-depth Life Cycle interpretation, focused on the potential role of soil modifications attributable to forest operations on the environmental profile in the analysed cycles, was carried out. Furthermore, an environmental comparison between the two systems was obtained considering technical differences involved. The entire analysis was based on a cradle-to-gate approach under a LCA perspective following the ISO 14040 guidelines (International Organization for Standardization, 2006).

3.2 MATERIALS AND METHODS

Life Cycle Assessment (LCA) is a standardised tool which allows assessing the potential environmental impacts related to the entire life cycle of a production system (International Organization for Standardization, 2006). In this study, two different systems of wood extraction following a cradle-to-gate analysis were assessed, starting from the forest felling to the biomass stocking, ready to be distributed. Considering the high variability in the market of wood biomass, due to the different strategies of marketing and distribution, further activities such as wood distribution from the factory to final users, use and disposal (e.g. ashes) were excluded.

3.2.1 Description of the study

In this study, the productive chain of wood biomass from coppices under regional-scale in Tuscany region was analysed. In particular, the main product obtained in coppice harvesting was firewood. Two different logging systems were evaluated in order to remark the differences in terms of environmental burdens. Tuscany region has a well-developed forest sector and a huge forest surface (about 50% of regional area) covering the 11.6% of the entire Italian forest surface ("INFC - National Inventory of Forests and Carbon sinks," 2005). The most common logging systems applied in coppices forest operations are:

- **Short Wood System (SWS)**: the final timber assortments are processed directly at the felling site and then extracted to the closest forest road, ready to be transported to the distribution or transformation sites. The thin material, tree tops and branches are left on the ground as soil improvements (Picchio et al., 2009).
- **Whole Tree Harvesting (WTH)**: each felled tree is entirely extracted to the closest forest road where it will be processed into the requested assortments, ready to be transported to the distribution or transformation sites. The logging residue is commonly recovered as biomass, generally as wood chips (Laina et al., 2013).

For each category (SWS and WTH) a reach variety of different extraction methods exists, characterised by different machines and techniques (Magagnotti et al., 2012; Schweier et al., 2015; Suchomel et al., 2012). In this study, two extraction systems were analysed, corresponding to the most common ones applied for SWS and WTH. Thus, ground-based extraction by tractor and bins was considered for cut-to-length firewood (SWS), and aerial extraction by cable-yarder was examined for whole tree (WTH). SWS and

WTH will be used hereinafter for referring at the specific extraction systems cited above.

3.2.2 System boundaries description

As previously reported, this study followed a cradle to gate approach. Therefore, the system boundaries included all forest operations carried out at the forest site as well as the biomass deposit in a factory. Further processes such as cross-cutting at final length (specifically for stove or fireplace - e.g. wood pieces of 30-50 cm length), log splitting, eventual packaging, distribution, use and ashes disposal were excluded from the study.

The common harvesting prescriptions in the analysed coppices were clear-cutting with or without release of standards (trees released in order to guarantee dissemination) depending on the tree species. Excluding industrial SRC, coppice forests in Italy, like in the majority of Mediterranean areas, are under extensive management and agronomic processes like ploughing, plantations, or fertilisations are not applied. For these reasons, the interventions are only related to logging operations (Suchomel et al., 2011). Considering SWS and WTH, the first produced only firewood, while in the second both firewood and wood chips were obtained. Industrial drying processes are not provided for firewood, which is normally sold by volume and not by weight. It is due to the uncertainty in revealing the real moisture content, which constantly changes (Piegai et al., 2004). However, the moisture content has a huge influence in weight and calorific potential of wood, and some reference tables are provided by different institutes (Hellrigl, 2006).

In the environmental assessment, the functional unit selected as reference for the different processes involved is “one ton of fresh wood at factory”. Firewood is generally measured in “stacked cubic meter” (st.m^3), which is the common commercial unit used in firewood market, defined as "*the volume (including voids) taken up by a stack of timber*" (Nieuwenhuis, 2000). However in this study, considering also wood chips as secondary product, the use of ton as functional unit was the best choice in order to obtain understandable and comparable results. For both systems (SWS and WTH) the conversion factors used were: i) density of fresh hardwood (Turkey oak and black locust) 0,90 kg/dm^3 (Giordano, 1981) and, ii) real wood volume in stacked volume 0,6 m^3/st.m^3 (Piegai et al., 2004).

Considering the generalised low amount of inputs related to motor manual operations (Berg, 1997), the transport of workers to the harvesting sites were included in the analysis, in order to evaluate the relevance of this input in the environmental profiles. In particular, we considered the number of workers involved in each operation as well as the working days spent in total. In the investigated operations, workers came to the work site by large size diesel cars, travelling four people maximum for each one. The average distance from the company meeting point to the forest work site, and return trip, was 40 km (average trip in related industries).

SWS - Ground-based extraction by tractor and bins of cut-to-length firewood system

After motor-manual felling, trees were processed by chainsaw in 1 meter length assortments (firewood) up to 6–8 cm as minimum diameter (Piegai et al., 2004); branches and the last thin part of the trunk were left on forest-ground, gathered in rows. During bunching, firewood logs were gathered in rows in order to facilitate the extraction phase when the worker load the wood into the bins mounted on a tractor. The extraction phase ended with the unloading of firewood at forest roadside. Then, firewood was loaded onto trucks by a loader mounted on a tractor. During truck loading one or two workers organized the logs on the platform in order to maximize the truckload. Finally, firewood was transported to the factory where it was stocked, eventually transformed (e.g. cut in smaller assortments) and sold to the distributors or directly to the final consumers. Three representative working sites located in southern Tuscany were considered for assessment considering 1 ha sample for each site in order to develop the complete data survey regarding productivity and consumption parameters. The main specie grown in the examined coppices is Turkey oak (*Quercus cerris* L.), with a sporadic participation of Downy oak (*Quercus pubescens* Willd.), Field maple (*Acer campestre* L.) and Manna ash (*Fraxinus ornus* L.). Normative prescriptions in this forest type allow the clear cut with a minimum release of 60 standards per hectare (Regione Toscana, 2010). In order to perform the analysis, the examined life cycle was divided in four main phases as displayed in **Figure 3.1**: i) SWS1 – Felling and Processing; ii) SWS2 – Extraction; iii) SWS3 – Loading; iv) SWS4 – Transport

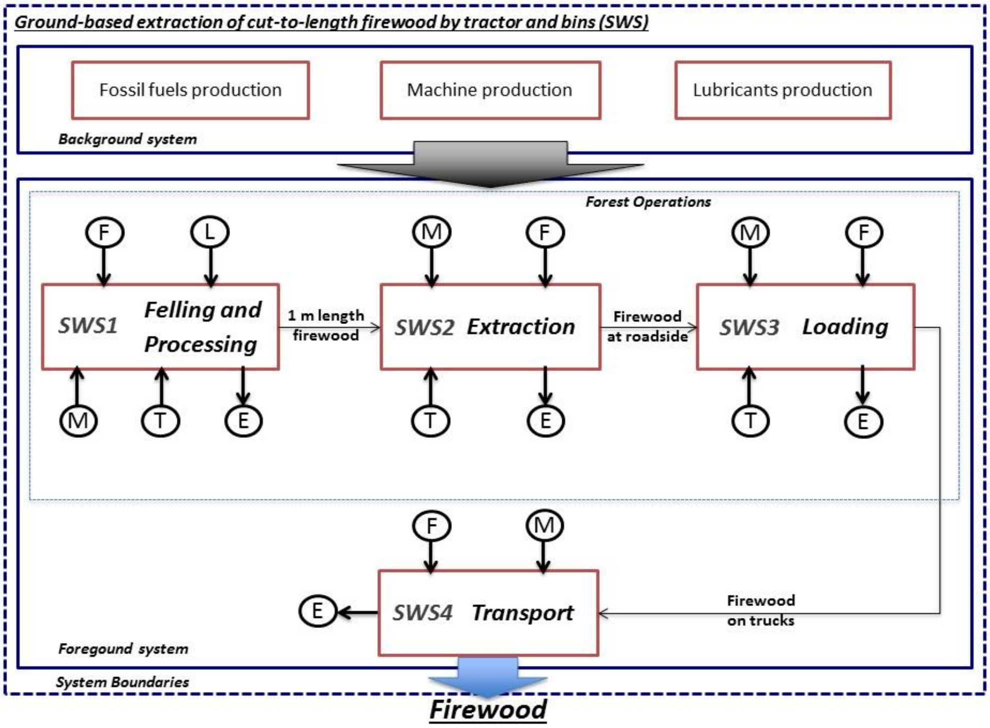

Figure 3.2. *Flow chart and system boundaries for ground-based extraction of cut-to-length firewood by tractor and bins system (SWS). Acronyms: F=fuel production (gasoline/diesel), L=chain oil production, M=forest machines production, maintenance and disposal; T=transport of workers; E=combustion emissions.*

WTH – Aerial extraction by cable-yarder of whole trees

As in the previous system, the trees were motor-manually felled by chainsaw, but not directly processed in the forest. The whole tree was extracted by cable-yarder to the landing site, next to the forest road. A mechanised processing phase involved an excavator equipped with a processor-head used for debranching and cross-cutting the tree in 1-meter length firewood assortments. After processing, firewood was loaded onto trucks in the same way as in SWS, while the branches and the thin tops of trees were chipped with a mobile chipper powered by a tractor. Wood chips were directly loaded during chipping phase on a truck and followed the same way to the factory. Two products are commonly obtained in WTH. The main one is firewood and the secondary one, wood chips. The main forest specie grown in examined coppices under this regime is Black locust (*Robinia pseudoacacia* L.). Normative prescriptions allow the clear cut without standards release for black locust, and impose the cutting prohibition for the other sporadic species as, in this case, Sweet Chestnut (*Castanea sativa* Mill.) and Manna ash (*Fraxinus ornus* L.) (Regione Toscana, 2010). In this analysis, the system was organised in seven different phases as displayed in **Figure 3.2**: i) WTH1 – Felling; ii) WTH2 – Extraction; iii) WTH3 – Processing; iv) WTH4 – Loading; v) WTH5 – Transport (for firewood); vi) WTH6 – Chipping; vii) WTH7 – Transport (for chips).

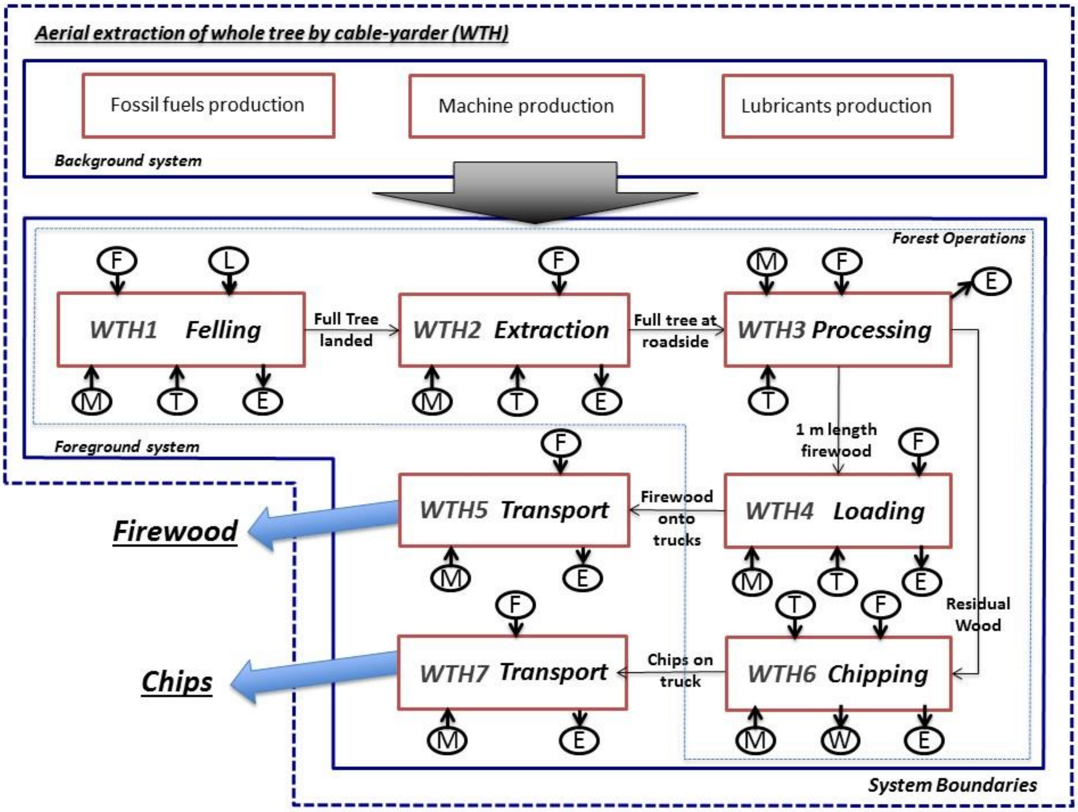

Figure 3.3. *Flow chart and system boundaries considered in aerial extraction of whole tree by cable-yarder system (WTH), with firewood and wood chips as main and secondary products respectively. Acronyms: F=fuel production (gasoline/diesel), L=chain oil production, M=machines production, maintenance and disposal; T=transport of workers; E=combustion emissions.*

3.2.3 Inventory data collection

As previously described, the two systems under investigation have different characteristics and involve different machines. Generally in the areas with a maximum slope of 30–40%, the SWS is the most used technique. In steep terrain, where the tractor cannot operate, the WTH become the best option (Hippoliti, 1997). The chosen working sites have different slope gradient but similar characteristics in terms of volume and number of trees, which allow obtaining comparable results. The main inputs in the analysed case studies were related to the use and the production of forest machines. Life Cycle Inventory provided a complete set of information, resumed in **Table 3.1** and **Table 3.2** for SWS and WTH, respectively. Primary data corresponded to field data collected by means of field surveys and questionnaires with forest workers. For each system we collected data on three hectares harvested; the mean results reported refers to one hectare. Productivity calculations, derived from field samples during forest operations by means of work times study (COST Action FP-0902, 2012), indicated the productive machine hour without delays (PMH_0) (Suchomel et al., 2012, 2011). Real measurements on fuel and oil consumptions of machines were directly collected during forest operations.

In particular, data collected corresponded to productivity as well as fuel and oil requirements for all the machines involved throughout the different production processes reported in Figures 3.1 and 3.2.

Table 3.1. *Summary of productivities, fossil fuels consumption and machines specifications in Short Wood System (SWS), referred to 1 ha of non-industrial coppice forest (average fresh firewood production 96.1 t/ha).*

Phase	Operation	Machinery	Power	Weight	Productivity	Fuel	Fuel consumption [a]	Operation hours	Wood processed	Lifespan	Repair coefficient	Average distance
SWS1	Felling and Processing	Chainsaw	3.5 kW	5.6 kg	8.50 st.m^3/h	Gasoline[d]	1.13 kg/h	20.9 h	178 st.m^3	2000 h[b]	0.7[b]	-
						Chain oil[c]	0.56 kg/h					
SWS2	Extraction	Tractor	85 kW	4750 kg	7.95 st.m^3/h	Diesel[f]	3.44 kg/h	22.4 h	178 st.m^3	10000 h[b]	0.8 [b]	530 m
		Bins	-	650 kg						4000 h[b]	0.75 [b]	
SWS3	Loading on Trucks	Tractor	91 kW	5520 kg	9.6 t/h	Diesel[f]	1.80 kg/h	10.0 h	96.1 t	10000 h[b]	0.8 [b]	-
		Grapple	-	1170 kg						4000 h[b]	0.75 [b]	-
SWS4	Transport	Lorry	-			Diesel[f]		-	96.1 t	540000 km	-	20 km

[a] *referred to net hour productivity;* [b] (Hippoliti, 1997)*;* [c] *density 0.92 kg/l* (STIHL AG & Co, 2011)*;* [d] *density 0.74 kg/l* (Nemecek and Kagi, 2007)*;* [f] *density 0.84 kg/l* (Nemecek and Kagi, 2007)*; st.m^3= stacked cubic meters*

Table 3.2. *Summary of productivities, fossil fuels consumption and machines specifications in Whole Tree Harvesting (WTH) referred to 1 ha of non-industrial coppice forest (average production 75.6 t of fresh firewood and 22.7 t of fresh wood chips).*

Phase	Operation	Machinery	Power (kW)	Weight (kg)	Net Productivity	Fuel	Fuel consumption ^{a}	Operation hours	Wood processed	Lifespan	Repair coefficient	Average distance
WTH1	Felling	Chainsaw	3.5 kW	5.6 kg	19.9 st.m^{3}/h	Gasoline^{d}	0,93 kg/h	9.1 h	182 st.m^{3}	2000 h^{b}	0.7^{b}	-
						Chain oil^{c}	0,46 kg/h					
WTH2	Extraction	Cable yarder	104 kW	5300 kg	6.2 st.m^{3}/h	Diesel^{f}	3.26 kg/h	29.5 h	182 st.m^{3}	10000 h^{b}	0.8^{b}	270 m
		Mainline	-	190 kg						600 h	0	
		Skyline and Guylines	-	780 kg						5000 h	0	
WTH3	Processing	Excavator	71 kW	16000 kg	6.9 t/h	Diesel^{f}	5.2 kg/h	14.2 h	75.6 t	10000 h^{b}	0.8^{b}	-
		Processor head	-	790 kg					22.7 t			
WTH4	Loading on Trucks	Tractor	85 kW	4850 kg	8.5 t/h	Diesel^{f}	2.2 kg/h	8.9 h	75.6 t	10000 h^{b}	0.8^{b}	-
		Grapple	-	870 kg								
WTH5	Firewood transport	Lorry				Diesel			75.6 t			20 km
WTH6	Chipping	Tractor	90 kW	5100 kg	8.7 t/h	Diesel	4.2 kg/h	2.6 h	22.7 t	10000 h	0.8	
		Chipper	-	3500 kg								
WTH7	Chips transport	Lorry							22.7 t			20 km

[a] *referred to net hour productivity;* [b] (Hippoliti, 1997)*;* [c] *density 0.92 kg/l* (STIHL AG & Co, 2011)*;* [d] *density 0.74 kg/l* (Nemecek and Kagi, 2007)*;* [f] *density 0.84 kg/l* (Nemecek and Kagi, 2007)*; st.m^{3}= stacked cubic meter*

Furthermore, an overall summary concerning the principal inputs and outputs for the two investigated systems, and referred to the functional unit, is reported in **Table 3.3**.

Secondary data were only managed for background processes. Secondary data correspond to specific bibliography and ecoinvent database ® (Frischknecht et al., 2004; Prada et al., 2015; Spinelli et al., 2009) regarding tailpipe emissions from fuels use in forest machines, production of machinery and fuels as well as activities and cars related to forest workers transportation (Picchio et al., 2009; Piegai, 2000; Spinelli and Magagnotti, 2014). The ecoinvent processes ® involved in this study were reported in **Table 3.4.**

Table 3.3. *Summarised table with the most representative input and output flows regarding 1 t of freshwood at factory gate for each system under assessment. "p" means the amount of machine requirement per phase considering the lifespan and the time spent per functional unit.*

Inputs from technosphere	Unit	SWS		WTH	
		Phase	Quantity	Phase	Quantity
Diesel	kg	2, 3	0.99	2,3,4,6	2.47
Gasoline	kg	1	0.246	1	0.087
Chain oil	kg	1	0.122	1	0.043
Chainsaw	p	1	$1.09\cdot10^{-4}$	1	$4.65\cdot10^{-5}$
Tractor	p	2	$2.33\cdot10^{-5}$	-	-
Bins			$5.82\cdot10^{-5}$		
Cable Yarder	p	-	-	2	$2.99\cdot10^{-5}$
Main line					$4.96\cdot10^{-4}$
Sky/guy lines					$5.97\cdot10^{-5}$
Processor	p	-	-	3	$1.45\cdot10^{-5}$
Tractor	p	3	$1.04\cdot10^{-5}$	4	$1.18\cdot10^{-5}$
Grapple			$2.60\cdot10^{-5}$		$2.95\cdot10^{-5}$
Tractor with chipper	p	-	-	6	$1.16\cdot10^{-5}$
Transport	t·km	4	20	5,7	20
Worker transport	km	1,2,3	4.62	1,2,3,4,6	3.70
Outputs to technosphere					
Firewood	t	4	1.00	5	0.77
Chips	t	-	-	7	0.23
Outputs to environment					
Emissions into air					
Carbon dioxide	kg		11.904		15.932
Carbon monoxide	g		211.9		114.7
Emissions into water					
Sulphate	g		191.1		216.9
Chloride	g		167.0		164.6

Table 3.4. *List of the main ecoinvent database ® processes (Frischknecht et al., 2004; Jungbluth et al., 2007; Nemecek and Kagi, 2007) considered in this study.*

Phase	Input	Ecoinvent database ® process
SWS 1 **WTH 1**	Chainsaw ψ	Power saw, without catalytic converter {RER}| market for | Conseq, U
	Gasoline	Petrol, two-stroke blend {GLO}| market for | Conseq, U
	Chain oil ψ	Vegetable oil, refined {GLO}| market for | Conseq, U
	Chains	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Conseq, U
SWS 2	Tractor ψ	Tractor, 4-wheel, agricultural {RoW}| production | Alloc Def, U
SWS 2	Bins ψ	Agricultural machinery, tillage {RoW}| production | Conseq, U
WTH 2	Cable Yarder ψ	Mobile cable yarder, trailer-mounted {GLO}
SWS 3	Tractor ψ	Tractor, 4-wheel, agricultural {GLO}| market for
SWS 3	Grapple ψ	Agricultural machinery, general, production/CH/I U
SWS 4 **WTH 5, 7**	Truck 25 t payload	Transport, freight, lorry >32 metric ton, EURO4 {RER}| transport, freight, lorry >32 metric ton, EURO4
WTH 4	Tractor ψ	Tractor, 4-wheel, agricultural {GLO}| market for
WTH 4	Grapple ψ	Agricultural machinery, general, production/CH/I U
WTH 6	Tractor ψ	Tractor, 4-wheel, agricultural {GLO}| market for
WTH 6	Grapple ψ	Agricultural machinery, general, production/CH/I U
SWS 2, 3 **WTH 2, 3, 4, 6**	Diesel	Diesel {Europe without Switzerland}| market for | Alloc Def, U
SWS 1, 2, 3 **WTH 1, 2, 3, 4, 6**	Worker transport	Transport, passenger car, large size, diesel, EURO 4 {RER}

ψ Process modified with primary data listed in **Table 3.1** and **Table 3.2**

3.2.4 Life Cycle Impact Assessment methodology

The software SimaPro 8.0.2 (PRé Consultants, n.d.) was used for the computational implementation of inventories in order to perform the environmental assessment for the analysed scenarios. The characterisation factors from ReCiPe Midpoint v1.12 (Goedkoop et al., 2013) method were applied for the following impact categories: Climate Change (CC), Ozone Depletion (OD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Photochemical Oxidants Formation (POF) and Fossil Depletion (FD).

3.3 RESULTS

Measurements after processing phase have shown that the total firewood harvested per hectare was 96.1 t in SWS and 75.6 t in WTH. While firewood was the unique product in SWS, in WTH 22.7 t of fresh wood chips were also obtained. In **Table 3.5** results regarding emissions for the considered impact categories are reported, both for SWS and WTH. SWS showed a better environmental profile than WTH in all impact categories, with lower emissions.

Table 3.5. *Impact assessment results for SWS and WTH for firewood production (per 1 t of fresh wood as functional unit)*

		SWS	WTH
Climate Change	kg CO_{2eq}	12.64	16.72
Ozone Depletion	mg CFC-11_{eq}	2.14	2.72
Terrestrial Acidification	g SO_{2eq}	66.6	97.3
Freshwater Eutrophication	g P_{eq}	2.36	2.90
Marine Eutrophication	g N_{eq}	7.60	10.3
Photochemical Oxidants Formation	g $NMVOC_{eq}$	155	157
Fossil Depletion	kg oil_{eq}	4.31	5.65

The contributions of different work-phases to each impact category are shown in **Figure 3.3.** Wood extraction had the higher impacts in all the impact categories examined, except for POF in SWS, where "felling and processing" was the phase with the highest estimated impact. The heavy machines (tractor and cable yarder) used in extraction phases had the lowest net productivity, which implied higher fuel and machine consumptions than in the other phases. The high number of hours worked and high fuel requirements caused the high values in each impact category. Regarding POF and the high contribute related to "felling and processing" phase in SWS, it was related to the production of petrol used in chainsaw, which is responsible of high emissions of NMVOC.

Regarding WTH, extraction stage reported the highest environmental impacts in the analysed cycle in all impact categories taken into account, including POF (Figure 3.3). The lower NMVOC emission in FTS are related to the lower number of hours worked by chainsaw, which is used only for felling while processing is made by a processor.

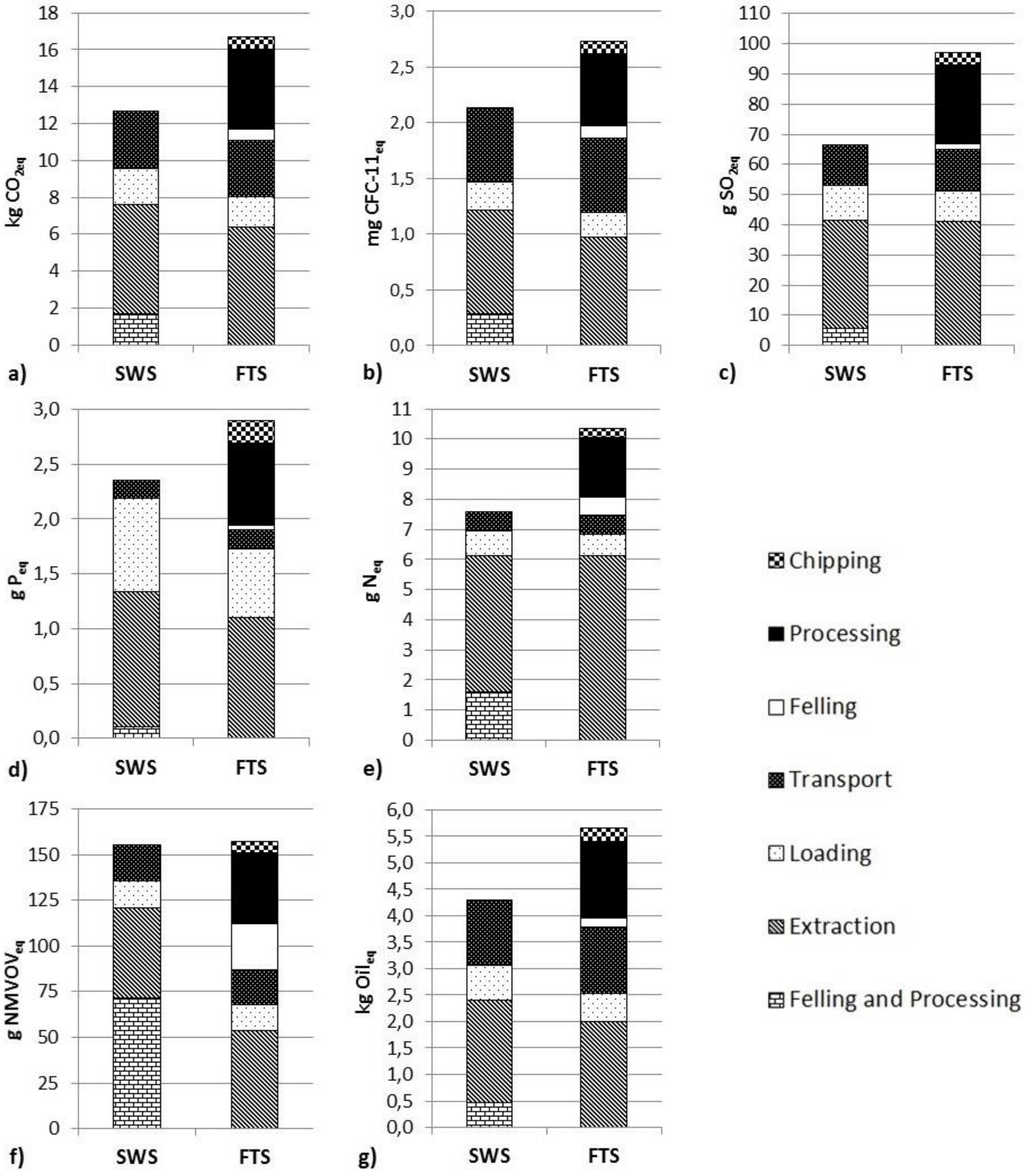

Figure 3.3. *Comparative distribution of environmental burdens per impact category, analysed system and involved stages throughout the corresponding life cycles. a) Climate Change; b) Ozone Depletion; c) Terrestrial Acidification; d) Freshwater Eutrophication; e) Marine Eutrophication; f) Photochemical Oxidants Formation; g) Fossil Depletion.*

3.3.1 Climate Change (CC)

The total amount of CO_{2eq} derived from the production of 1 t of fresh wood transported to the factory in SWS was 12.64 kg. The 47% (5.9 kg CO_{2eq}) of these emissions were concentrated on the extraction phase, which was also the one that required the highest energy requirement in terms of fossil fuels. In fact this phase has the highest fuel consumptions and CO_{2eq} emissions are strictly related with diesel combustion. Firewood transport from roadside to the factory was responsible for the 24% of total CO_{2eq} emissions and the remaining flow was distributed between loading (16%) and felling and processing (13%). In WTH, the total CO_{2eq} emission was higher than in SWS and corresponded to 16.72 kg CO_{2eq}. The extraction phase was again the main responsible stage (38% of total contributing substances) followed by the processing stage (26%). The transport covered the 18% of CO_{2eq} emissions and loading the 10%. Felling and chipping stage had a lower role in this impact category (4% each). Two different reasons are related with the low emissions in felling and chipping phases. The first one is characterized by a motor-manual operation with higher net productivity and lower fuel consumption than other phases. Moreover, chainsaw is a light-weight machine with lower impacts attributable to background processes than tractor or processor used in the other phases. The second one, chipping, had low emissions because this phase involved only a limited fraction of total biomass processed on the total, being wood chips a secondary product in the analysed system, which were obtained only from treetops and branches.

Considering the different processes included in the different phases, it is interesting to underline that the transport of workers to the work site (considered for all the phases) covered the 14% of total CO_{2eq} emissions in SWS and the 10% in WTH, where a lower number of workers and work-hours were required.

3.3.2 Ozone Depletion (OD)

For this impact category the potential impact was reported as trichlorofluoromethane equivalent emissions (kg CFC-11_{eq}), with a total amount of 2.14 mg in SWS and 2.72 mg in WTH. Extraction was the environmental hotspot and covered the 43% and the 36% of emissions in SWS and WTH, respectively. In these cases diesel production had the main role in increasing emissions, and it is confirmed by the fact that the phases with the highest impacts are the ones with higher diesel consumptions. This is the reason why in SWS, the transport had an important role with 31% of emissions, while loading (12%) and felling and processing (13%) had a lower relevance. In WTH, Processing and Transport phases equally contributed to cover a half of total emissions, while the rest was divided between loading (8%), chipping (4%) and Felling (4%), phases with lower diesel consumptions. The transport of workers, as in CC, was responsible of 14% and 10% of total emissions for SWS and WTH respectively.

3.3.3 Terrestrial Acidification (TA)

In this impact category the extraction covered more than a half of SO_{2eq} emissions in SWS (54%), while firewood transport, loading, and felling and processing were responsible for 20%, 18% and 8%, respectively. Among these phases, transport of workers had a lower impact in relation to the previous impact categories, with 8% of total SO_{2eq} emissions. In WTH the trend was similar, the operation as environmental hotspot was the extraction with 42% of total emissions. An important role in this impact category was covered by processing (27%), wood transport (14%) and loading (11%). Transport of workers emitted only the 5% of total SO_{2eq}. Emissions related to diesel combustion were the principal contributors in TA, followed by machine production, and it explains the showed results. In fact, the phases with the highest diesel consumptions –extraction first- were the main responsible of contributions to this category.

3.3.4 Freshwater Eutrophication (FE)

Considering eutrophication potential, the first impact category we analysed was "freshwater eutrophication". In this impact category the results showed how the use of heavy machines had a key-role on total emissions. In SWS the total amount of emission obtained was $2.36 \cdot 10^{-3}$ kg P_{eq}, which was concentrated mainly in extraction (52%) and in loading (36%), while in transport and during felling and processing only the 7% and the 4% respectively were emitted. In WTH extraction (38%), processing (26%) and loading (22%) covered almost the total amount of P_{eq} emissions, while chipping (7%) and transport (6%) had a marginal role and felling (1%) contribute was negligible. The transport of workers was responsible for the 15% and for 11% of total emissions in SWS and WTH, respectively. According to the results, impact burdens were mainly related to machine production. It explained the higher impacts related to the phases were tractor, cable yarder and processor were involved, considering that these were the biggest machines used in the analysed work systems.

3.3.5 Marine Eutrophication (ME)

The second category considered on eutrophication was related to marine water, and the unit used in the results was kg N_{eq}. For both SWS and WTH the hotspot phase for this impact category was extraction with the 59% of total emissions, which were $7.60 \cdot 10^{-3}$ and $1.04 \cdot 10^{-2}$ kg N_{eq} respectively; both production and use of machines were the main contributors to the total emissions. In SWS there was an important contribution of felling and processing with the 21% of emissions, attributable to the use of the vegetable oil used for chain lubrication. Loading and transport had a lower importance with a contribution of 11% and 8% respectively. Beyond the extraction in WTH the processing phase had a huge contribution in emissions (19%), mainly due to the same reasons of higher impacts in extraction, while the rest was distributed on the other phases: Loading (7%), transport (6%), felling (6%) and chipping (3%). Regarding the transport of workers, it was interesting how it covers the 16% (SWS) and the 10% (WTH) of total emissions.

3.3.6 Photochemical Oxidants Formation (POF)

This category evaluated the emission of Non-Methane Volatile Organic Compounds (NMVOCs); in SWS the emission related to the production of the functional unit were estimated in $8.38 \cdot 10^{-2}$ kg NMVOCs, in WTH were similar, $8.49 \cdot 10^{-2}$ kg. In SWS the contribution of each work phase in this impact category was different in comparison with the previous ones. Felling and processing showed a contribution of 46% of total and the extraction was not the environmental hotspot, however it had a huge percentage of emission (32%) on the total. The highest value obtained in felling and processing is due to the combustion of gasoline blend, which is characterised by high emissions of NMVOCs. Transport (12%) and loading (10%) had the lowest impact in POF. Regarding WTH, extraction had the highest contribution, as in the previous impact categories, and processing covered the 25% of total emissions; felling phase emitted the 16% of NMVOCs, which is relevant considering the low amount of hours worked in chain-sawing in WTH. In this category the transport of workers on the work site gave a minimum contribution to the total amount of NMVOCs (3% for both SWS and WTH).

3.3.7 Fossil Depletion (OD)

This impact category was strictly related to the use of fossil fuels, for these reasons the work phases characterised by the use of heavy machines were the ones with the higher impacts in fossil depletion potential. In particular, in SWS extraction emissions were 45% of the total, transport covered the 29%, while the operations with a higher manual contribution showed lower impacts with a 15% of total kg oil_{eq} in loading and 11% in manual felling and processing with chainsaw. In WTH, extraction was the hotspot too, contributing for 35% on total amount; processing and transport covered respectively the 26% and 22% of depletion potential, while loading (9%), chipping (4%) and felling (3%) had lower importance.

3.4 DISCUSSION

Results showed how the impacts related to the examined forest operations systems were mainly related to extraction phase. As we can appreciate in Tables 3.1 and 3.2, net productivities reached the lowest values during extraction. The consequence was a higher consumption of fossil fuels and a higher contribution in terms of use of heavy machines in order to process the biomass. In fact, while in the phases as felling and loading, wood was moved on short distances, extraction was the phase where wood was moved in an average of hundred meters in a natural context. For these reasons, there were the highest requests in terms of power of machines and fuels. Comparing total values and the relative contribution of each phase in the analysed systems, the study showed how SWS had lower environmental burdens in all the categories examined than WTH. This was mainly due to the largest use of heavy machines in WTH (e.g. processor), instead of the manual and semi-mechanised processes involved in SWS (e.g. processing by chainsaw), which permitted to improve productivities and to reduce the working time. However a reduced operation time involved a lower number of working hours for workers and it influenced the amount of inputs related to the transport of workers to the work site. Interesting information derived from the examined results was the relevance of workers transportation to the work site. In SWS the average quota of environmental burdens in the different impact categories was 12% of total, and reached the 16% in Marine

Eutrophication. Extraction was the phase with highest values of emissions deriving from the transport of workers both for SWS and WTH; this was due to the high number of hours and workers required in this phase comparing to the others. In WTH, the general contribution of this process was lower than in SWS, with an average value of 8%, and a maximum of 11% in Freshwater Eutrophication. The differences highlighted in the analysed extraction systems showed a better environmental profile of SWS than WTH. On the other hand, extraction of full trees with cable yarder allows harvesting wood biomasses in areas where there are not technical possibilities to collect wood by tractor with bins. An interesting evaluation on extraction phase may be the analysis of impacts on soil related with the transit on forest ground. In this study an approach to this topic using bibliographic data was developed, as explained in the next subsection.

3.4.1 Changes in soil emissions after forest operations

There is an interesting bibliography related to the effects of forest operations on soils, and in particular of machines transit, which suggested some considerations. The transit of machines and wood logs generate several impacts, well resumed in Cambi et al. (Cambi et al., 2015). The effects of transit generate physical and chemical modifications in forest soils (Picchio et al., 2012a), with a consequent variation in natural substances' cycle. In particular an increment in N_2O emissions and a reduction in CH_4 absorption by forest soil has been measured (Butterbach-Bahl et al., 1997; Cambi et al., 2015; Teepe et al., 2004). No specific data were directly collected in this study regarding the modifications in soil properties after forest utilization. However in order to understand if emissions from soil could significantly change the results in terms of environmental burdens previously shown, a scenario considering soil emissions was developed for both SWS and WTH, implementing data from bibliography. Climate Change impact category was assessed, considering N_2O and CH_4, with a conversion factor in CO_{2eq} of 296 for N_2O and 23 for CH_4 ((IPCC) International Panel on Climate Change, 2001). Soil compaction attributable to tractor transit and to trees dragging in SWS and in WTH respectively, causes higher N_2O emissions and a reduction of CH_4 absorption from soil. After forest operations in WTH, the average surface ratio with damages, due to cable yarding, was estimated in 13.5% of total (Lucci, 1987); in SWS there is a higher surface ratio involved in compaction attributable to the different work method and the quality level in work organization. In this study, soil compaction was estimated in 30% of total surface for SWS, considering a tractor trail each 10 meters along the harvested area. The period with altered soil emissions in comparison with natural conditions was considered as one year long, assuming that after this period values become normal again. Values of emissions from Teepe et al. (Teepe et al., 2004) were chosen taking into account the soil conditions in our study areas. These emissions values (given in “mg $N_2O{\cdot}m^{-2}{\cdot}y^{-1}$” and “mg $CH_4{\cdot}m^{-2}{\cdot}y^{-1}$”) were reported in our case study considering the compacted surface, the conversion values for CO_{2eq} and the wood production in tons in order to return results referred to the functional unit (ton of fresh wood). This emission was allocated to extraction phase. For WTH 0.512 kg CO_{2eq} were estimated as additional emissions from soil compaction, corresponding to a 3% increment of total emissions (8% considering only extraction). In SWS 1.254 kg CO_{2eq} from disturbed soil correspond to the 10% of total emissions (21% considering only extraction phase). Especially in SWS, emissions due to damaged soil were relevant. Moreover in this type of operation, there was huge quality variability in techniques and organisation of working sites, which implied a related variability in the traffic on forest surface. This had an important influence on soil emissions. In SWS the surface ratio of 30% was an average between the best practice (quantified in 15%, corresponding to a trail each 20 m) and a not-organized work that could damage almost all the surface. It is interesting to underline that comparing only extraction phases in SWS and WTH and considering soil emissions, the first one derived on higher impacts than the other, which was the opposite result obtained without taking into account soil damages. SWS extraction could be environmentally better than WTH only in the best scenario mentioned above, where damaged surface was limited to 15% of total harvested surface. However, overall results showed a better environmental profile for SWS than WTH in both cases (with and without considering soil emissions). In particular, WTH could result with a better profile than SWS in terms of total CO_{2eq} emissions only when the damaged surface in SWS would be more than 98% of the total surface.

3.5 CONCLUSION

Wood biomasses will be strategic in the near future as renewable energies, in order to reduce the use of fossil fuels and consequently reducing the dangerous emissions. On the other hand, there are also environmental impacts related to wood harvesting, transformation, use and disposal, which need to be quantified. This study made a comparison by means of LCA between two of the most common work system for forest operations in coppice under traditional management. Results showed how the use of heavy machines in WTH, fuelled by fossil fuels (e.g. in processing phase), were responsible of higher environmental burdens than in SWS, characterised by a higher use of manual and motor-manual operations. However, two aspects have to be considered comparing SWS and WTH. Despite the better environmental profile of SWS, WTH allows harvesting in steep terrain, while SWS is limited to slope up to 30 – 40%. Moreover, the higher mechanisation level in WTH guarantees a higher safety level for forest workers than SWS, improving also the ergonomics in forest operations (Albizu-Urionabarrenetxea et al., 2013).

An interesting result emerged in this study was the relevant role in environmental burdens related to the transport of workers, especially for SWS, where the emissions related to the travel of workers to the work site was responsible for an average of 10% of all the impact categories considered.

Moreover, interesting developments were related with results included in the discussion section, concerning changes in soil emissions after forest operations. The described scenarios derived from the implementation of data from bibliography (Butterbach-Bahl et al., 1997; Cambi et al., 2015; Picchio et al., 2012a; Teepe et al., 2004). However, this analysis showed that soil emissions due to traffic disturbance could have significant effects on environmental burdens investigations. For these reasons, some detailed studies on soil emissions after forest operations should be recommended in order to allow inserting relevant and reliable data in LCA studies focused on wood.

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CHAPTER 4

Identifying causes, dynamics and consequences of work accidents in forest operations in an alpine context

ABSTRACT

Forest operations are recognized as one of the most dangerous works in all the productive sectors. In a sustainable perspective, where wood perfectly responds to environmental needs, we cannot disregard social sustainability and the related health and safety of forest workers. The aim of this study was the analysis of the accidents records in public companies in the Province of Trento, in Northern Italy, regarding forest operations in the period 1995–2013. Several information were available thanks to the up-to-date accident books compiled by each company. With an average Frequency index in the examined period of 88 injuries per million hours worked, forest operations were confirmed as one of the most dangerous works along all productive sectors. Monday had a significant higher frequency of accidents comparing to the other weekdays. The age of the workers seemed influencing the recovery period after injuries, which exponentially increase at rising age. Felling and processing definitely resulted as the most dangerous activity in forest operations covering the 31% of total accidents happened. '*He puts a foot wrong…', 'He was hit by…'* and *'He was hit with…'* are the most common phrases used in describing the studied accidents; these were the action cause of the accident and contribute explaining why body extremities, first of all the hands, were the body parts most injured. Finally, a new concept in accident analysis was proposed introducing the analysis of 'recidivism', which analysed the eventual recurrence of accidents to the same worker in a given period. Results were interesting and underlined that some workers had more than one injury during the analysed period, up to seven for one of them.

Keywords: *health and safety, ergonomics, recidivism, Monday, severity*

4.1 INTRODUCTION

Forests supply several environmental, social and economics good and service for people and society worldwide. Among the other, wood production is one of the most important functions of forests in many areas, and in order to guarantee a sustainable production of woody products a sustainable forest management is required. A sustainable forest management should guarantee the best safety and health conditions for people who directly work in forests. Forest operations are considered the most dangerous job in all fields of production (Albizu-Urionabarrenetxea et al., 2013; Bentley et al., 2005; Klun and Medved, 2007; Köh et al., 2010; Lindroos and Burström, 2010; Rhee et al., 2013; Tsioras et al., 2011). Risks related to forest operations are firstly due to worksite environment, which implies uncommon factors of risks in comparison with the most part of other jobs (Bolognesi et al., 2013; Hippoliti and Piegai, 2000). The main risks related to worksite environment are: i) terrain conditions; ii) weather conditions, and in particular high and low temperatures, wind, ice, snow and rain; iii) biological agents. Other risks related to forest operation are due to: use of machines and tools; exposure to heavy loads; exposure to physical agents (noise, vibration); exposure to wood dust and exhaust gasses (Bolognesi et al., 2013; Hippoliti and Piegai, 2000; Hippoliti, 1997). Heinimann (Heinimann, 2000) highlighted the fundamental importance of social aspects in forest operations, in particular on health and safety of forest workers.

Several studies already produced interesting analysis based on statistical data on risk and injuries collected in different situations and countries. These studies evaluated the work conditions (Ahola et al., 2013; Bush et al., 2014; Canto et al., 2007; Wilmsen et al., 2015), the accidents occurred during forest activities (Bentley et al., 2005; Lilley et al., 2002; Lindroos and Burström, 2010) or during specific logging systems in forest operations (Bentley et al., 2005; Montorselli et al., 2010; Poschen, 1993;

Shaffer and Milburn, 1999; Tsioras et al., 2011; Wang et al., 2003). Considering accident analysis, there is a lack of information regarding southern European countries in comparison with the better-studied events in central and northern countries (Albizu-Urionabarrenetxea et al., 2013; Tsioras et al., 2014). Interesting case study were also developed in New Zealand (Bentley et al., 2005; Gaskin and Parker, 1993), United States (Shaffer and Milburn, 1999; Wilmsen et al., 2015) and China (Wang et al., 2003). A fundamental difference between occasional wood cutters in comparison with professional ones has been underlined by Fischer (Fischer et al., 2005).

The increase of mechanization level in forest operations contributes in reducing both the risks and the frequency of accidents and/or occupational diseases (Bell, 2002). In fact, today the modern machines permits to work in better conditions in terms of ergonomic and safety than in the past. However not always high mechanization may be applied, both for management and/or technical reasons. In particular, there are technical and environmental limitations often attributable to the terrain slope. Even if a high mechanized ground-based machines for extraction already exists, also for steep terrain (Visser and Stampfer, 2015), sometimes there are some restrictions to their use, mainly related to environmental risks. Especially in high populated countries as Italy, where forests are mainly located on mountainous areas (Alps and Apennines), and several restriction related to environmental protection are applied, high mechanization is relatively uncommon (Picchio et al., 2010). On the Alps cable-based technologies have been the backbone of steep-slope harvesting (Bont and Heinimann, 2012). For these reasons motor-manual felling (Montorselli et al., 2010) and extraction by tractor with winch and cable yarder are the most common work systems adopted by forest companies (Picchio et al., 2010).

In this study the interest was focused on professional workers, in an area were a mix of high and medium mechanization level is applied. In Italy forests cover more than 36% of total surface (‘INFC – National Inventory of

Forests and Carbon sinks,' 2005) and forest sector has a fundamental role in terms of economics and environment (FOREST EUROPE, 2015). In Italy, the 'National Institute for Insurance against Accidents at Work (INAIL)' provides data in relation to forest activities and related injuries, but often the information are aggregated with agriculture (Italian National Institute for Insurance against Accidents at Work (INAIL), 2015a). Moreover, despite the good structure of archives, available specific information regarding forest operations were mainly incomplete. For this reason, a lack of information regarding accidents during forest operations exists. Considering the high risks related to this job, a deep analysis regarding injuries occurred during works in forest could have a key-role in order to develop new solutions for accident reduction in this field. The aim of this study was to analyse in deep the registered work accidents occurred in a representative Italian forest area, in order to identify the different causes, dynamics and consequences of accidents, which commonly affect forest workers during forest operations and related activities. Moreover, in this study not only strictly defined operations with specific machines and techniques (i.e. extraction by cable yarder) were examined, but all the operation that a forest worker could make during his career in the analysed area. In particular, different parameters of the accidents were analysed, identifying the most important factors of risk.

4.2 MATERIALS AND METHODS

Data collection regarded different public companies located in northern Italy, distributed in the Autonomous Province of Trento, on the Alps. These companies are all included in one of the most known Italian forest areas characterised by a very well developed forest sector. Each company directly manage different public forests. For these reasons each company directly hire forest workers, who all work generally in the same forest conditions and with the same mechanization level. As in Austrian case (Tsioras et al., 2011), also in Italy both public and private companies must have and compile an accident book, where all injuries occurred to company's worker have to be registered (Italian Republic, 2008). This prescription must be attended only when the accident implies three or more days of prognosis, however the companies included in this study registered also the injuries with minor severity. In this study, data registered from 1995 to 2013 were considered. Sensitive data have been managed following law prescriptions and the information from the four analysed companies were aggregated in order to agree with the request of companies to avoid comparison between them. Considering terrain steepness and the forest management practices which characterise these areas, motor-manual felling and cable logging are the most common and convenient logging systems applied (Spinelli et al., 2015). Beyond steep terrain, also weather conditions increase risk level during work. All forest workers had been offered the proper Personal Protective Equipment (PPE) for each operation. Moreover, forest operators followed training periods focused on the specifics tasks to be performed by each one.

Accident books were generally compiled collecting information on the event date, accident dynamics and consequences. Starting from the description of each event in the accident book, the information for developing the analysis were extracted and summarized in the following categories:

- **Worker's age**, the distribution of accidents in relation with worker's age classes of 10 years extent were examined. In particular 6 classes of age were identified: i) <20 years old; ii) 21–30 years old; iii) 31–40 years old; iv) 41–50 years old; v) 51–60 years old; vi) >60 years old. Kruskal-Wallis test was applied to identify differences between age classes in workdays lost. Moreover, workdays-lost variation in relation with workers' age was investigated through linear regression models.

- **Work operation**, divided in: 'Felling and processing', 'Bunching and extraction', 'Forest road construction/maintenance', 'Wood handling', 'Moving in forest', 'In itinere' and 'Other'. 'Other' includes all the activities, still related to forest operations, which could not be assimilated to the other ones.
- **Injuries severity.** Five classes were established on the basis of the number of workdays lost due to the injury: 'Minor injury', less than 8 days lost; 'Moderate injury', from 8 to 25 days of prognosis; 'Serious injury', between 26 and 60 days lost; 'Severe injury', from 61 to 100 workdays lost and 'Highly severe injury', for accidents which implied more than 100 days without working.
- **Material agent cause of the event**, identified in order to understand which were the most dangerous elements, materials and tools. Ten categories were resumed identifying accidents caused by: *i)* 'Gr' =forest ground; *ii)* 'BS'= boulder, stone; *iii)* 'LST'= log, stump, tree; *iv)* 'BT'=branches, top; *v)* 'SFt'= splinter, fragment of tree; *vi)* 'C'= chainsaw; *vii)* 'OE'= other equipment (sickle, pruning hook, hatchet); *viii)* 'Bio'= biological agents (tick, wasp, snake, etc.); *ix)* 'MV'= machines and vehicles; *x)* 'Ot'= other, including all that is not included in previous categories.
- **Kind of injury**, made following Italian codification (Italian National Institute for Insurance against Accidents at Work (INAIL), 2015b): W=wound; C=contusion; DSPM=dislocation, sprain, pulled muscle; F=fracture; AL=anatomic loss; LIAP=lesions from infectious agents

and parasites; OA=other agents; FB=foreign body; LS=lesions due to strain.

- **Body parts injured**, made dividing body in 4 main areas: i) 'Head', which included cranium, face and eye; ii) 'Upper extremity', including shoulder, arm, elbow, hand and wrist; iii) 'Central body', which included hip, rib cage, back, torax and trunk; iv) 'Lower body', including leg, knee, gluteus, feet and ankle.
- **The action cause of the accident**, organized following Italian codification (Italian National Institute for Insurance against Accidents at Work (INAIL), 2015b): i) 'He went in contact with…'; ii) 'He was hit with…'; iii)'Lifting up/moving something'; iv) 'He puts a foot wrong…'; v) 'Incoordinate movement'; vi) 'He was hit by…'; vii) 'Something ran over him'; viii) 'He was bit by…(animal)'; ix) 'He was bit by…(insect)'; x) 'He was pressed by…'; xi) 'He felt down…'; xii) 'He was driving…'.

Temporal analysis regarding the day of the week of the accidents and the workers' age were also done.

Only one fatality was registered in the analysed period. Considering the low statistical value of one event, it was not included in the overall analysis.

In order to understand if, in each of the different aspects analysed, there were a significance in frequency distribution the statistical test 'chi-square' were applied through the open source software named 'R' ('The Comprehensive R Archive Network,' n.d.).

Not always all the information for the total registered injuries were available. It caused a variation in the total number of accidents taken into account in the different aspects considered. The sample dimensions were always reported in results description.

Different aspects on frequency, severity and dynamics were investigated in order to obtain the most precise analysis of phenomena's involved. In particular general information as frequency and severity indexes were calculated following Italian standards for statistics on occupational injuries

(UNI, 2007). In particular the frequency index (FI) and the severity index (SI) were calculated as in the formulas below:

$$FI = \frac{n_i}{H} \cdot 10^6$$

where n_i is the number of injuries occurred and H is the total number of hours worked.

$$SI = \frac{D}{H} \cdot 10^3$$

where D is the total number of days of prognosis prescribed to the injured workers, and H is the total number of hours worked.

An important aspect to manage during the analysis was the number of workers that changed during the years, attributable to the general reduction of public employers. Also considering the different months of each year, the number of workers changed because of the seasonal workers. For these reasons an average number of 1200 hours$\cdot$year$^{-1}\cdot$worker^{-1}, calculated on the basis of the total hours of work for each type of contract, was assumed for calculating the frequency index and as a reference value.

4.3 RESULTS AND DISCUSSION

A total of 385 injuries were examined in the period 1995–2013. All the injuries caused temporary disease except one, which was a fatality. The average frequency index was 88 injuries per million hours worked, with a maximum value in 2003 of 142 and a minimum of 47 in 2006 and 2012. Regarding the severity index the average value in the period 1995–2013 was 1.87 working days lost per thousand hours worked, with a maximum of 3.96 in 1996 and a minimum of 0.55 in 2012. A decreasing trend over time was recorded for both SI and FI (**Figure 4.1**), even though any statistical significant relation was found.

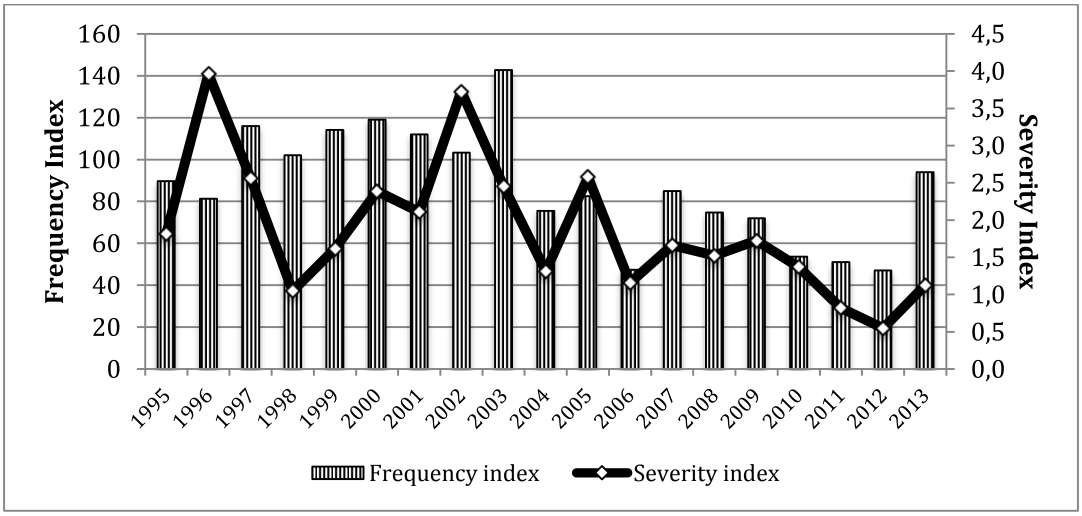

Figure 4.4*: Frequency and Severity indexes trends in the examined period*

The distribution of events during the week was examined (375 injuries in total). Usually, the working week started on Monday and ended on Friday; however, a reduced number of workers, for different operational reasons, sometimes worked also on Saturday and some accidents happened also in this day (1% of the total). Monday was the day with the highest number of accidents (98 injuries, 26.1%), while Wednesday the one with less events registered (57 injuries, 15.2%). Chi-squared test was applied considering all the week days, including Saturday, and the results showed a significance difference in frequency distribution with a confidence interval of 99% ($X^2=78.42$, df=5, $p<0.000$). However, considering the low interest on Saturday, due to the differences in total work hours than the other days, and the high influence of low values on results, the chi-squared test was applied also excluding Saturday. Result still showed a significant difference in distribution ($X^2=12.62$, df=4, $p<0.013$), with a p-level of 95%. These results were in line with other studies regarding the high number of accidents happened on Monday (Shaffer and Milburn, 1999; Tsioras et al., 2011, 2014). But in relation with the lowest value obtained for Wednesday this is in contrast with the information found in bibliography where Wednesday is one of the days with the highest frequency of injuries (Albizu-Urionabarrenetxea et al., 2013; Shaffer and Milburn, 1999; Tsioras et al., 2011). Monday resulted the most dangerous day likely because at the beginning of the working weeks the operators approach their activity with a lower attention and carefulness than in the others days of the week. In this context the lowest value on Wednesday could be related to an easier achievement of concentration during the central day of the week, when distractions of the past weekend are as far as the perspective of the next one.

The distribution of accidents in relation with worker's age classes of 10 years extent were examined. The information was available for 292 accidents (76% of total). The majority of the events affected workers between 31 and 50 years old. However, this information has a limited value considering that there were not available data regarding the age of the entire cohort of workers, including those that were not injured during the considered period. For this reasons it was impossible to calculate a percentage between the number of workers injured and total workers for each age class. Nevertheless, the distribution of the average workdays lost per injury in each age class (**Figure 4.2**) showed an increasing trend in relation with the raising age. This was probably attributable to the lower rehabilitation capacity of an older person in comparison with a younger one, those increasing the average number of days of prognosis after an accident. The results of 'Kruskall-Wallis' test suggested to investigate the relation between the workers' age and the lost workdays, even if the p-value obtained was not properly significant (p-value=0.05895). However, the regression analysis did not show significant results.

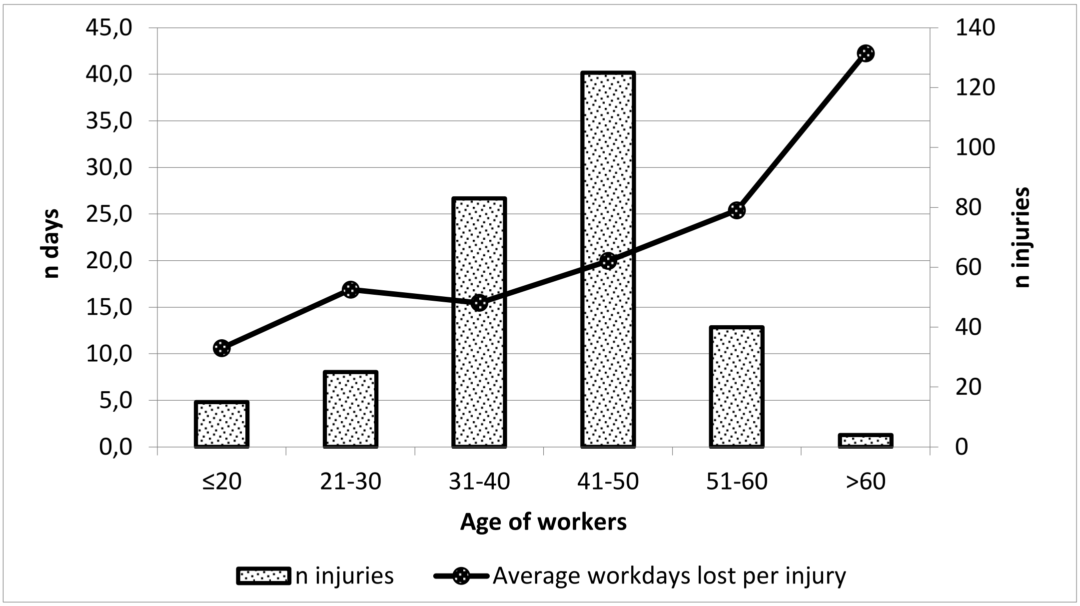

Figure 4.2.: *distribution of injuries in age classes, with related average of workdays lost per injury*

The highest number of injuries happened during felling and processing phase (31% of total accidents), which was significantly more frequent than in the other phases identified (X^2=163.82, df=6, p<0.000). As shown in **Figure 4.3**, among the other forest operation phases there were not significant differences. However, about one fourth of total events happened during other operations, which differ from the ones properly considered as forest operations.

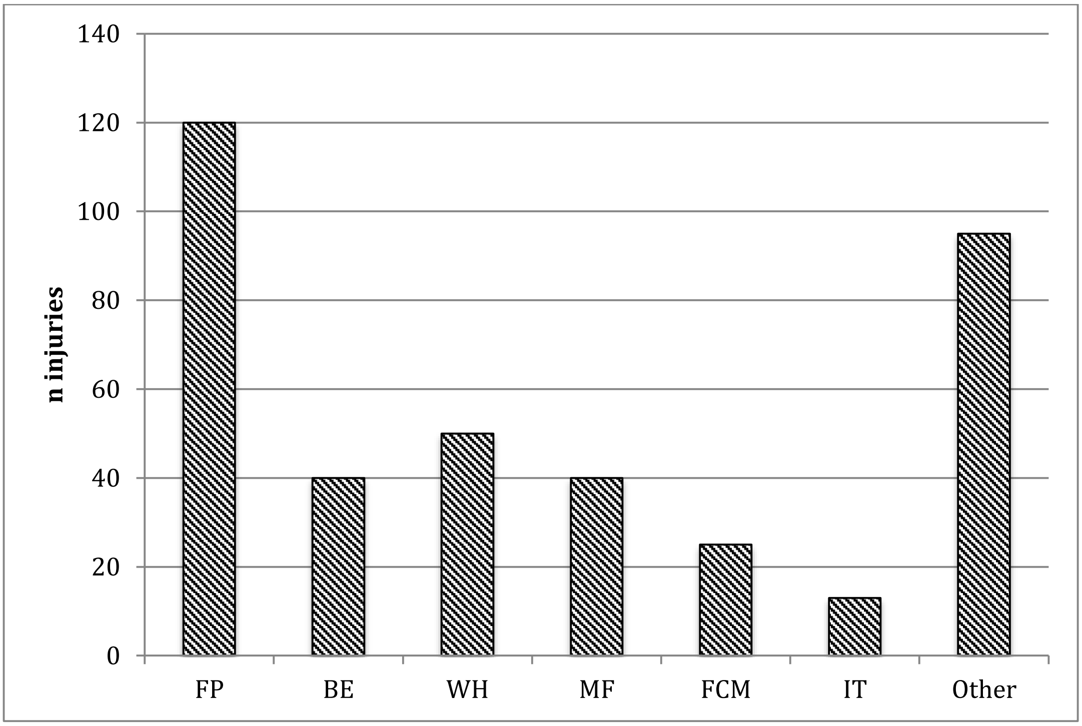

Figure 4.3: *Distribution of injuries by type of operation done at the accident happening. FP=felling and processing; BE=bunching and extraction; WH=wood handling; MF=moving in forest; FCM=forest road construction/maintenance; IT= in itinere; Other.*

The distribution of accidents is uneven across the kind of injury (X^2=397.59, df=8, p<0.000). 'Contusion' was the most frequent kind of injuries resulted, which includes more than one third (36%) of total injuries (379), followed by 'Wound' (23%) and 'Dislocation, sprain, pulled muscle' (16%). All categories were shown in **Figure 4.4**, which included also the related information regarding the severity, indicated by the average number of workdays lost, for each kind of injury. Regarding the three most common kinds of injury the average damage is similar, around 15 workdays lost per injury, while 'Fracture' has a limited frequency in the overall collection of injuries but it is the one that implies the highest number of workdays lost (63.9 average of workdays lost per injury).

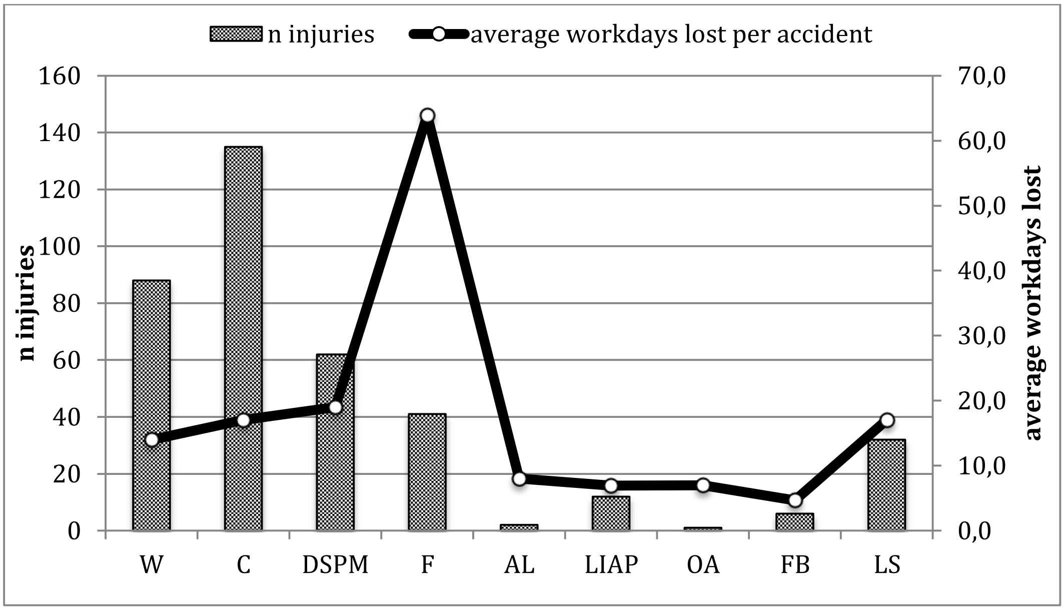

Figure 4.4: *accidents distribution regarding the kind of injury, and average damage for each category expressed by the average workdays lost. W=wound; C=contusion; DSPM=dislocation, sprain, pulled muscle; F=fracture; AL=anatomic loss; LIAP=lesions from infectious agents and parasites; OA=other agents; FB=foreign body; LS=lesions due to strain.*

The actions which caused the accident, analysed following Italian standards (Italian National Institute for Insurance against Accidents at Work (INAIL), 2015b), were identified in 17 categories. The 75% of the actions were classified in three categories: i) the most represented was '*He puts a foot wrong…*', which covered the 33% of total accident. This dynamics generally implied the worker's fall, attributable to the work on natural ground, and the common consequences were contusions and dislocations; ii) the second one was '*He was hit by…*' (27% of total accidents), which were commonly events characterised by the loss of control of logs or other materials; iii) '*He was hit with…*' were common events (14% of total), generally characterised by errors in the control of work tools, during which the operator hit himself, i.e. with hatchet or chainsaw.

Chi-squared test applied to the material agent of the injury showed a significant difference (X^2=161.93, df=9, p<0.000) in frequencies distribution. Forest ground resulted to be the most frequent cause of injury with the 27% of the total injuries. Despite the use of professional boots with a proper sole design, sliding on natural ground is a common problem and frequently implies falls and consequent injuries. Whole trees or parts of them (i.e. logs or stump) caused the 14% of total injuries. However, as shown in **Figure 4.5**, LST was the agent of injuries causing the highest average value of workdays lost (34 workdays), followed by MV (27 workdays), even though this category showed a quite low frequency (8%). Chainsaw, which is frequently considered the most dangerous tool involved in forest operations, was the material agent in 7% only of the examined events, with an average value of 18 days of prognosis per injury. This result is mainly attributable to the use of proper PPE, thus avoiding serious injuries.

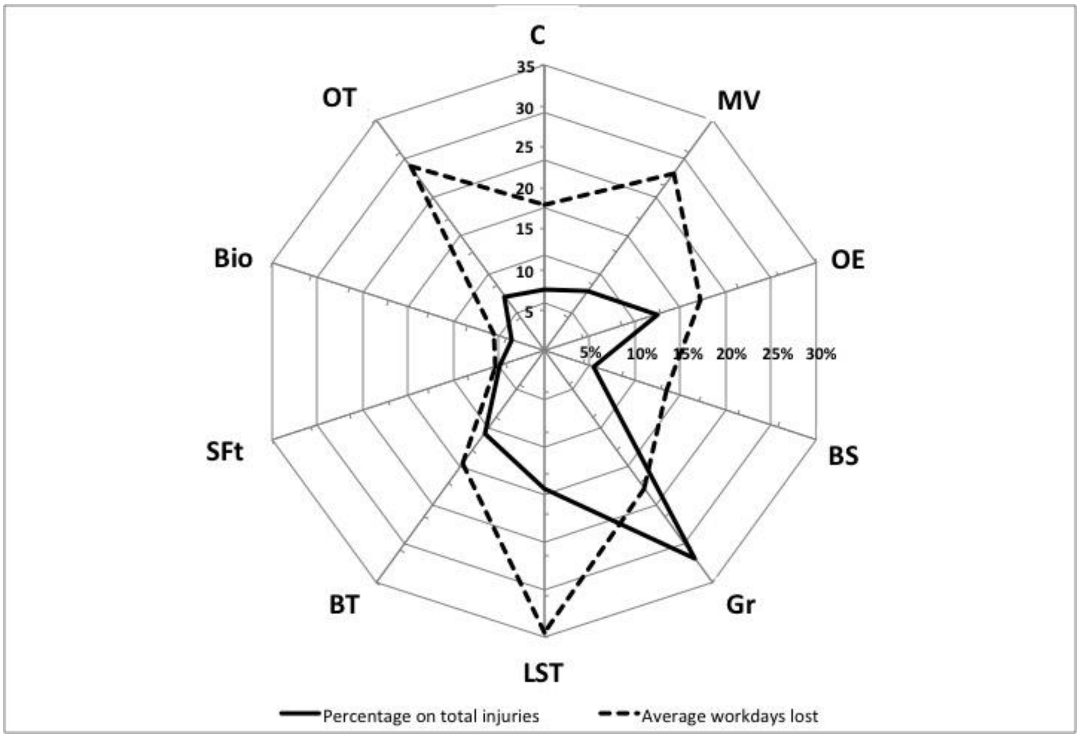

Figure 4.5: *percentage distribution of injuries depending on the agents that caused the accident and related average of workdays lost per category. 'Gr' =forest ground; 'BS'= boulder, stone; 'LST'= log, stump, tree; 'BT'=branches, top; 'SFt'= splinter, fragment of tree; 'C'= chainsaw; 'OE'= other equipment (sickle, pruning hook, hatchet); 'Bio'= biological agents (tick, wasp, snake, etc.); 'MV'= machines and vehicles; 'Ot'= other.*

The analysis of the body parts affected by injuries highlighted how extremities were the most susceptible to be damaged during work. As reported in Table 4.1, upper and lower extremities were injured in 65% of the accidents. Within the body parts, the hand had the higher incidence of injuries. However, the worst consequences of injuries were reported for elbow, which showed an average period of 46 days of prognosis.

Table 4.1: *distribution of injuries in body areas and body parts.*

BODY AREA	n	% ON TOTAL	BODY PART	N	% ON TOTAL	AVERAGE WORKING DAYS LOST PER INJURY
HEAD	67	18%	*CRANIUM*	30	8%	13
			FACE	5	1%	6
			EYE	32	8%	6
UPPER EXTREMITIES	117	31%	*SHOULDER*	9	2%	28
			ARM	21	6%	15
			ELBOW	5	1%	46
			HAND	70	19%	21
			WRIST	12	3%	21
CENTRAL BODY	65	17%	*HIP*	5	1%	20
			RIB CAGE	6	2%	23
			BACK	24	6%	17
			TORAX	17	5%	23
			TRUNK	13	3%	34
LOWER EXTREMITIES	128	34%	*LEG*	42	11%	34
			KNEE	45	12%	25
			GLUTEUS	3	1%	8
			FEET	18	5%	37
			ANKLE	20	5%	16

A general overview regarding accident severity, described by the average number of working days lost attributable to the consequences of injury, showed that moderate injuries (from 8 to 25 days of prognosis) were the most common in forest operations (48% of total survey; $X^2=267.92$, $df=4$, $p<0.000$). Merging also minor injuries, these two categories represent about 75% of total accidents, which correspond to the 37% of total workdays lost. 'Serious' injuries were the 17% of total events, including the 28% of total workdays lost, while 'Severe' and 'Highly severe' accidents covered 5% and 2% of total injuries, respectively, corresponding to 17% and 18% workdays lost. These information underlined how there is a high risk potential in forest operations, and how it is relatively common to incur in serious or worst accidents, including fatalities. In fact, we have to consider in our analysis also the fatality occurred in the analysed period. Moreover, the relatively low number of 'Severe' and 'Highly severe' injuries should not be underrate. In fact, despite the low number of total injuries, these categories included more than one third of total workdays lost.

In 175 accidents a unique ID code, which identifies the workers, was available. It permitted to identify the recidivism of some operators. In fact results showed that only 121 workers were involved in 175 accidents. In the considered period, 83 (69%) workers were involved in a single event, 28 (23%) of them were injured two times and 8 (7%) three times. The recidivism level culminated with two workers who were involved in accidents five and seven times. Despite this information were available only for a minor quote of events examined, results still permitted to verify that in a context where safety rules are always accomplished (e.g. training, PPE, certified machines), personal behaviours had a key-role in risk potential. In this context, a higher attention and assessment of the employer in assigning the different task to the different workers should be required. In fact, considering the different workers' attitudes may help in reducing the injuries number and effect. When continuative training programs and reprimands have no effects on worker’s behaviour, the employer should intervene assigning low-risk tasks to the worker.

Furthermore, some consideration concerning the unique case of dead happened in the considered period. This tragedy happened during extraction with cable yarder, when a log hit the operator. This information have no statistical value but it is useful to underline, once more, that forest operations have a high-risk potential.

Considering that the analysed data were collected for public employers, the next challenge for the future should be to obtain information regarding accidents in forest operations by private companies. This should improve our knowledge enlarging our perspective in an almost unknown reality, though it covers an important part of total accidents. Another interesting topic to be analysed in further researches would be the analysis of the near misses (McKinnon, 2012) in forest operations, which should contribute in better understanding the limits of safety conditions in forest.

4.4 CONCLUSION

Forest operations are characterized by a high accident frequency, which labelled this job as one of the most dangerous. A forest worker operates in open-air areas, on natural ground, under variable and sometimes extreme weather conditions, and above all he works with machines, trees and logs, which are dangerous in cutting and heavy to manage. Certainly, this series of different elements finally contributes in a rising of risks related to the works in forest. However, wood already has a key-role in our life and its extraction is fundamental for our Society, and in the future this needs will be stronger than now in an increasing sustainable perspective. At the same time, guaranteeing Health and Safety to the workers is a mandatory task in order to satisfy the social sustainability of wood productions. For these reasons it is necessary to work in reducing as much as possible the accidents rates, especially in areas, like forest operations, where this rate reaches huge values. In this context, research must play an important role for understanding phenomena and proposing solutions in techniques, organization and development. Studies focused on accidents analysis are fundamental in order to understand in deep the causes, the dynamics and the consequences of injuries. In particular, this study gave a precise overview, in a large temporal window, of accidents in a productive area on Italian Alps. As other studies remarked, despite the huge number of accident analysis in forest operations there were a lack in analysis in semi-mechanized operations, especially in mountainous areas. Moreover it is fundamental to develop studies where all the types of injury are analysed, including injuries with light consequences in terms of days of prognosis, and including also injuries in operations not properly classified as forest operations, but still made in forest-related activities by forest workers. Research results are fundamental for improving the work organization, the training of workers and the attention of the forest managers in order to reduce accidents where safety prescriptions have the worst performances. Moreover, in PPE development it is fundamental to know that some parts of the body are more susceptible of injuries than other.

A relatively new and important aspect is related to accident recidivism. This is an aspect that has not been previously studied, but it is fundamental in understanding and quantifying the workers with behaviour prone to injuries. In this context, the analysis of the occurred injuries may lead to the development of specific training programs aimed at reducing wrong approaches to working tasks, thus improving health and safety and reducing recidivism.

The biggest problem in this kind of analysis is to find consistent information regarding both quality and quantity. In fact, even if requests of information were submitted to public companies, which should be the reference for attending safety procedures, it is often very hard to obtain a complete and not censored dataset. In particular, for recidivism analysis it should be necessary to have the names or the unique codes of injured workers in order to analyse the eventual inclination of some workers to injuries. This problem is amplified with private companies, especially in Italy where the average dimension of forest companies is smaller in comparison with other countries. In conclusion, the main challenges for the future in accident analysis in forest operations should be both the study of small private companies, and the analysis of 'near misses'.

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CHAPTER 5

A methodological approach exploiting modern techniques for forest road network planning

ABSTRACT

Forest roads have a key role in forest management. A well-developed road network allows all forest activities, including wood harvesting, fire-fighting and recreational activities. However, forest road construction and maintenance involve economic and environmental costs. For these reasons, forest road network planning is a fundamental phase of forest management, maximizing the benefits and reducing costs and impacts. In the last few years, thanks to modern technologies in data collection both for terrestrial and forest characteristics information, new methods and tools have been developed to improve and facilitate road planning. The aim of this study was the development of a specific Decision Support System for helping managers during forest road network planning, exploiting Multi-Criteria Analysis, an Analytic Hierarchy Process and Geographic Information Systems. Three main steps characterised the study: i) an in-depth survey of the existing forest road network; ii) an accessibility evaluation, based on a commonly applied Italian definition, taking into account the morphological characteristics of the land; iii) an estimation of the accessibility requirements through the analysis of experts' opinions, defined as Road Needs Index, based on different factors that commonly influence managers during the planning phase. These phases were applied to a real forest property located in northern Italy, and some improvements were proposed simulating a manager's approach during planning, using the results obtained. The results showed interesting features in accessibility evaluation, which identified three different classes of accessibility (served, barely served and not served), represented in a map. The estimation of Road Needs Index assigned to each forest management unit a class regarding road requirements: low, medium, high and very high. This information was merged, becoming a useful tool to identify the forest areas with the highest problems in relation to the forest road network. **Keywords:** *forest management; GIS; Analytic Hierarchy Process; accessibility; road needs.*

5.1 INTRODUCTION

A sustainable perspective in forest management cannot ignore careful and accurate forest road network planning (Çalişkan, 2013; Hippoliti, 1997, 1976). A forest road network traditionally ensures access to forests and grazing lands, allowing forest operations and other productive activities. In the last decades, the increasing importance of the multi-functionality of forests has highlighted the key role of forest roads management for tourism and recreational tasks (Chirici et al., 2003; Gumus et al., 2008). Moreover, forest roads allow access to remote areas in case of natural hazards (Enache et al., 2013) and are a fundamental infrastructure in forest fires extinguishing (Hayati et al., 2012). Construction characteristics should be different, depending on the kind of machines that are expected to run on the different road branches. In particular, width, slope and radius of curvature are the most important elements for forest roads that can limit vehicles' trafficability (i.e. dimensions and payload of vehicles). The quality of roads is related to building and maintenance quality, in terms of both techniques and materials, and it can vary during road lifespan (Kiss et al., 2015). Considering these aspects, an accurate road network plan is mandatory to allow the best efficiency and cost effectiveness of forest roads for all forest activities. Despite the essential role of forest roads in forest management, several potential negative effects exist in relation to these infrastructures. Despite the reduced width and excavation volume of a forest road in comparison with public roads, several environmental impacts relating to its construction, maintenance and use should affect this infrastructure (Avon et al., 2010; Delgado et al., 2007; Demir, 2007; Trombulak and Frissell, 2012), especially taking into account the natural context where it is located. However, these impacts can be reduced thanks to accurate planning and management (Akbarimehr and Naghdi, 2012). Furthermore, forest roads should be considered also as ecosystems with an active role in the forest environment, which is not necessarily always negative (Lugo and Gucinski, 2000). For these reasons, a well-designed and well-developed road network plan must support the forest management plan to permit the best maintenance and enhancement of the road network, focused on the real management needs, through an integrated information exchange. Taking into account the different interests related to forests, many analyses under various viewpoints have to be considered during planning. The main aspects under consideration should regard technical, economic and environmental issues. A technical approach identifies the strengths and weaknesses in the current road network to permit the best application of the management plan. Economic implications always have fundamental impacts; in the forest sector, the construction of a road is a significant cost (Ghajar et al., 2012; Samani and Hosseiny, 2010) and accurate planning permits optimization of the cost effectiveness of road network management and enhancement. There are some fundamental steps that characterise a well-developed forest road network plan. i) A complete knowledge of the actual conditions of each road segment in the entire network examined, both in terms of construction characteristics and maintenance conditions. ii) A cautious evaluation of the actual accessibility state of the different forest areas. iii) An evaluation concerning the real needs of forest roads–i.e. at management unit level–in the different sub-areas of the managed area, considering all of the functions provided by the analysed forest, such as wood production, hydrogeological protection, nature conservation, tourist interests and landscape tasks. The best system in forest management planning, where different needs have to be considered, is the development of a Decision Support System (DSS). In the last few years, this system has made possible an organised and integrated overview of relevant parameters related to forest functions, helping forest managers in decision processes (Vacik and Lexer, 2014). In this context, considering the huge number of variables to be considered to represent the main interests related to forest multi-functionality, the approach of a Multi-Criteria Analysis (MCA) is recommended (Çalişkan, 2013; Sacchelli et al., 2013a). Moreover, the Analytic Hierarchy Process (AHP) (Saaty, 1980) has been, and continues to be, one of the most common DSSs in defining the priority of different parameters considered, organizing them in a hierarchy (Çalişkan, 2013). Furthermore, Geographical Information Systems (GISs) play a key role in managing and displaying terrestrial data for spatial forest planning (Zeki Baskent and Keles, 2005) and specifically also in forest road planning (Dean, 1997; Hayati et al., 2012; Mohtashami and Bergkvist, 2012; Najafi and Richards, 2013). These approaches and technologies are widely used in forest planning under a sustainable perspective (Ducey and Larson, 1999; Miettinen and Hämäläinen, 1997) with a huge number of studies based on multi-criteria and hierarchical approaches, also on the specific topic of forest road planning (Ghajar et al., 2012; Pellegrini et al., 2013; Samani and Hosseiny, 2010). Because of the integration between terrestrial data and information included in the forest management plan, a valuable road network plan, which takes into account the most important aspects for road management, can be developed. With all of this organised information, it is possible to make informed choices in road maintenance, enhancement and building. Summarizing, short-term needs should not be the main influence in the construction of a forest road, but the intervention should be integrated in mid/long-term planning, to maximize the related functionality and economic benefits, minimizing the environmental impacts. The aim of this work was the development of an MCA integrating GIS and AHP to obtain a DSS with reliable information regarding accessibility and road needs, in a case study area in northern Italy. Moreover, an evaluation of the obtained results was performed; the results were used in simulating a forest manager's interpretation and identifying weaknesses in the road network. Hypotheses for enhancement and improvements in the analysed forest road network were defined and suggested to the managers.

5.2 MATERIALS AND METHODS

The study area was Paneveggio forest, an alpine public property located in the Autonomous Province of Trento, in northern Italy. The property has a total area of 4,300 ha, of which 2,803 ha are forests. Paneveggio is entirely included in a mountainous area above 1,300 m above sea level. Characteristic tree species are spruce (*Picea abies* (L.) H. Karst), larch (*Larix decidua* Mill.) and Swiss stone pine (*Pinus cembra* L.). A close-to-nature silviculture is applied in this area and the average annual yield is 6,000 $m^3 \cdot y^{-1}$ of roundwood. Paneveggio is included in the 'Provincial Natural Park of Paneveggio and Pale di San Martino'. The study was divided into three main parts to organize data collection and processing in sequential steps: i) Forest road network analysis; ii) Accessibility analysis; iii) Forest roads needs evaluation. These steps are described and illustrated below.

5.2.1 Forest road network analysis

The objective at this stage was the collection of all useful information regarding characteristics of the network, to implement an up-to-date database with geographical information, construction characteristics and maintenance level of each forest road. Each forest road was surveyed by car and several types of information were collected. With a set of basic instruments and a portable GPS, a survey form was filled in with the following main information: co-ordinates and altitude of starting and ending points, total length, maximum and average slope, prevalent and minimum width, minimum curvature radius of hairpin turns. Moreover, accessory elements such as water-bars, cross-drainage culverts etc. were counted and described. For each road, a general description, an evaluation of maintenance conditions and the identification of criticisms were added to the form and then to the dataset. All of the collected information was implemented on a GIS platform (both ArcGIS 9.3 and QGIS 2.10 software were used) and a shape file with up-to-date information for each road was obtained. Roads were represented as lines, merged by nodes in each road intersection. A Digital Terrain Model (DTM) and orthophotographs were helpful during graphic representation of forest roads to correct the errors in accuracy made by the portable GPS during the field survey. Because of the dimensional characteristics collected, it was possible to classify each road following the Italian classification suggested by Hippoliti (1976), which is related to the kind of machine that could drive on the road. Characteristics of the roads are reported in **Table 5.1.**

Table 5.1. *Road classification following Italian standards.*

		ROAD FOR TRUCKS		ROAD FOR TRACTORS
		MAIN	SECONDARY	
ROAD WIDTH	MINIMUM	3.5 m	3.0 m	2.5 m
	PREVALENT	5–6 m	4–5 m	3–4 m
SLOPE	OPTIMUM	3–8%	3–8%	3–8%
	MAX. AVERAGE	10%	12%	14%
	MAX. FOR SHORT STRETCHES	14%	18%	20 (25)%
	MAX. COUNTER SLOPE*	10%	12%	14%
MINIMUM CURVATURE RADIUS IN HAIRPIN TURNS		10 m	7 m	5 m

* counter slope is defined as a grade that is opposite to the general running grade of a road, i.e. the slope of the road section/s that tractors or trucks have to cover loaded.

All of the collected information was organized in a specific geo-referred database. The total length and road density (m·ha^{-1}) were calculated.

5.2.2 Accessibility analysis

In this phase, an in-depth analysis of forest accessibility was developed by means of GIS, thanks also to the information collected and organised in the first step of this work. First of all, it was necessary to define the criteria of forest accessibility in relation to forest roads. In detail, the method based on the access time, suggested by Hippoliti (1976), was applied. This method has been applied in other studies ((Cavalli and Grigolato, 2009; Chirici et al., 2003; Grigolato et al., 2013) because it is functional in mountainous conditions, it takes into consideration terrain slope variations. Hippoliti (1976) defined three different accessibility classes based on the time required for a forest worker to make a round trip on foot from the nearest road to a given point in the forest. This time was called the 'access time'. Hippoliti assumed an average walking speed for a worker in forest of 4 $km \cdot h^{-1}$ on flat terrain, and a walking speed of 400 $m_a \cdot h^{-1}$ on steep terrain, where m_a is the differential levelling in metres. When the access time is up to 30 minutes (for going in the morning and coming back at the end of workday) the area is classified as 'served', while when it is between 30 minutes and two hours, it is 'barely served'. When a worker spends more than two hours reaching the work site, the area is considered as 'not served' by the forest road network. This concept was introduced in the 70s, when the manpower price in Italy was very low. Nowadays, considering the cost of manpower, it is not economically viable to spend two hours to reach the work site. For that reason, in this work Hippoliti's approach was modified in time ranges, reducing the maximum access time to one hour for 'barely served' areas. The revised accessibility characteristics are summarized in Table 5.2.

Table 5.2. *Accessibility categories based on a revised definition of Hippoliti*

ACCESSIBILITY	ACCESS TIME (RETURN TRIP)	DISTANCE IN FLAT TERRAIN (WHEN SLOPE < 10%)	DIFFERENTIAL LEVELLING (WHEN SLOPE ≥ 10%)
SERVED	Up to 30′	Max 1000 m	Max 100 m
BARELY SERVED	Between 30′ and 60′	Max 2000 m	Max 200 m
NOT SERVED	More than 60′	More than 2000 m	More than 200 m

Three different methods to calculate and graphically represent the degree of accessibility in the Paneveggio forest were implemented. The classical method, based on a field survey and manual representation on maps, was implemented to identify the second best application in terms of accuracy and reliability. The descriptions of each method are reported below.

'Method H' manual approach

'Served' and 'barely served' areas were manually drawn starting from each road branch and considering altitude gaps (100 m for 'served' and 200 m for 'barely served' areas). Once the draft accessibility map was made, a field survey permitted correction of the map identifying natural barriers that impede access to some areas, e.g. cliffs and deep gullies. Finally, the results were manually reported on a GIS platform to obtain a digital map, comparable with the results of the other methods.

‘Method A’ travel time

This was the first GIS approach applied in this study for accessibility estimation. Hippoliti’s definition for accessibility could be described taking into account the travel time or travel distance. In this method the travel time was considered to determine the accessibility class for each point in the forest property (Chirici et al., 2003). This operation required several steps and information. A DTM with a resolution of 5 m × 5 m created from LIDAR data, and the road network map previously developed (see Section 2.1) was used as starting information. A ‘Cost Distance’ tool was applied to calculate the accessibility degree of the forest surface. In particular, this tool is a procedure for determining least cost paths across continuous surfaces, typically using grid representations (de Smith et al., 2015). In this study, Cost Distance identified the surface, around each forest road, with a maximum cost in terms of time of walking transfer for a forest worker. Therefore, several steps were made to obtain a ‘cost-map’ including the information concerning the crossing time for each pixel, which strictly depends on the slope gradient: **i)** slope map creation, starting from the DTM, in raster format containing the slope gradient in % for each pixel ($\boldsymbol{p_{\%}}$); **ii)** differential levelling ($\boldsymbol{d}$) covered for each pixel, was calculated considering a horizontal distance ($\boldsymbol{d_0}$) of 6 m (the average of the side of the pixel, 5 m, and the diagonal, 7 m), using the formula:

$$\text{differential levelling} = d = \frac{p_{\%} \cdot d_0}{100},$$

iii) ‘d’ was reclassified with high value (900 m) to exclude extreme slopes (>100%), that could not be crossed by walking. For slopes lower than 10%, a fixed value of 0.6 m was assigned to obtain efficient results for flat terrains too; **iv)** considering the climbing speed of 400 $m_a \cdot h^{-1}$, corresponding to $0.\bar{1}$ $m_a \cdot s^{-1}$ ($\boldsymbol{t_u}$), a raster containing information regarding the time of pixel crossing was made by the following equation:

$$\text{pixel crossing time} = \boldsymbol{t_{pc}} = \frac{d}{t_u} = \frac{\boldsymbol{d}}{\boldsymbol{0.\bar{1}}},$$

v) starting from the vector file of the forest road network, a raster file representing presence/absence of roads was created; **vi)** the Cost Distance tool was applied to define the 'served' and 'barely served' areas, starting from the raster of road presence and the cost-map previously created, applying the time limits as maximum cost (15 minutes and 30 minutes for 'served' and 'barely served' areas respectively).

'Method B' fraction of the maximum distance

In the previous method, 'Cost Distance' was applied considering the travel time. In this case, a method that interprets the accessibility definition considering the travel distance was developed. As explained in Section 2.2, on flat terrain we considered the linear distance covered, while on a slope we considered the change of altitude between the starting point at the roadside and the work point in the forest. A DTM of 5 m × 5 m in resolution guaranteed the morphological information. The Cost Distance procedure was applied also in this case, and several steps were necessary: **i)** a slope map ($p_{\%}$) based on DTM was created; **ii)** the slope map was reclassified, as in method A, to obtain a unique 'cost-map' efficient on both slope and flat terrain. Therefore, the values '10', to all the pixels characterised by a slope up to 10%, and the value '99999', to all the pixels with a slope higher than 100%, were assigned. **iii)** A 'weight' was given to each pixel, which was determined as the ratio between the maximum distance ($D_{\max}$) on flat terrain (1000 m) and the horizontal distance ($D_{f(p\%)}$) corresponding to the maximum differential levelling ($d_{\max}$) ('served' = 100 m, 'barely served' = 200 m) on a terrain with the slope of the pixel taken into account. Finally, the formulas for weight calculation were the following:

$$\text{weight} = w = \frac{D_{\max}}{D_{f(p_{\%})}}\ ,\ D_{f(p_{\%})} = \frac{100 \cdot d_{\max}}{p_{\%}},$$

iv) the final cost-map was obtained by multiplying the weight value by the pixel size; **v)** starting from the vector file of the forest road network, a raster file representing presence/absence of roads was created; **vi)** starting from the raster of road (presence/absence) and the cost-map previously created, applying the distance limits as maximum cost (1000 m and 2000 m for 'served' and 'barely served' areas respectively), the Cost Distance tool was applied defining the 'served' and 'barely served' areas.

'Method C' fixed distance buffer

This is an expeditious approach, which did not consider Hippoliti's definition of accessibility. It was implemented to compare a quick method with the other models described. It simply drew a buffer at a fixed distance from each road branch. Several examples of this accessibility evaluation have been developed in other studies, considering different distances in relation to the type of machines and techniques applied. Some studies set a unique limit value, e.g. 300 m without slope considerations (Bååth et al., 2002), and 3 km but limited to the first slope class (max. 20%) (López-Rodríguez et al., 2009). Moreover, in other studies, different classes with a varying distance were considered, comparing buffers within 150, 200 and 250 metres from the road (Pentek et al., 2008). In this study, two buffers were applied, the first in a range of 100 m from the road and the second in a range of 300 m. The first corresponds to the 'served' area, which was identified with the operative distance generally considered for extraction with tractor and winch. The second one was assumed as the 'barely served' area, which corresponds to the operative distances of a lightweight cable-yarder.

Finally, a comparison between the different methods was made. 'Method H' was considered as 'truth' to have a reference for comparison.

5.2.3 Forest roads needs evaluation

Thanks to the previous analysis, the accessibility degree for all forest management units was available. This was important information, but it needed to be integrated with another analysis, in a typical MCA perspective, to obtain a complete set of information useful for roads management. In particular it was fundamental to support accessibility information with the real needs of roads for each forest management unit. The 'needs of roads' (or 'needs of accessibility') aimed to identify the accessibility requirements in the different areas, concerning the different characteristics of forest management units and the related silvicultural prescriptions applied. Effectively, forest located at an altitude close to the upper tree line, with low tree growth and managed under a protective perspective, generally requires a lower accessibility level than others located in a more fertile area, with high yield, and managed under a productive perspective. In this context, a GIS-based method for evaluating the forest needs in terms of accessibility was developed. It was assumed that forest operations would be the forest-related activities characterised by the highest accessibility requirements, compared with the other services provided by the forest, and activities carried out inside it. Therefore, the methodology was developed considering factors related to forest productivity. On the basis of Paneveggio's forest management plan, a set of data was chosen as factors useful for determining the forest-road needs. Three categories were identified as more suitable than the others considering their reliability and the impact on this study: growing stock (*GS*), site fertility class (*FC*) and productive potential index (*PPI*) for high forests. Other factors were discarded for specific reasons, e.g. the annual volume increment, which should be a good indicator characterising a forest management unit in terms of productive capacity. In our case, the increment information presented some out-of-scale values, presumably attributable to mistakes in reporting, which did not guarantee a good reliability level. In particular, the three cited factors were chosen because: **i)** ***GS*** represented a reference point in a short-term productivity perspective; **ii)** ***FC***, which was divided into nine classes, from the most fertile (class '1') to the least fertile (class '9'), assigned to each forest management unit. It was chosen for representing a fixed condition along the time regarding the production capacity of each management unit; **iii)** ***PPI***, this was a classification made by a pool of experts regarding the whole Province of Trento. Following different parameters, including the main tree species, hydrogeological risks and environmental significance, they assigned to forest sub-areas a synthetic value representative of their productive potential. This index was divided into nine classes, from the lowest productive potential (class '1') to the highest (class '9'). This factor was chosen because it was relevant to a long-term management perspective.

To calculate a 'road needs index' (*RNI*), the factors, after normalization, were merged by means of a weighted sum. To assign a 'weight' to each factor, an Analytic Hierarchy Process (AHP) was applied to the results of local forest expert interviews. Each factor was normalized (in a range between 0 and 1) following the processes explained below:

-*Growing Stock (GS):* considering the distribution of *GS* values, we applied an exponential function for *GS* values up to 700 $m^3 \cdot ha^{-1} \cdot y^{-1}$, with increasing values from 0 to 1; for *GS* values higher than 700 $m^3 \cdot ha^{-1} \cdot y^{-1}$, the normalized value assigned was always 1:

$$GS_{\text{norm}} = \begin{cases} -0.00000198835 \cdot GS^2 + 0.00280713 \cdot GS + 0.0093 \text{ , for } 0 \leq GS \leq 700 \\ 1 \text{ , for } GS > 700 \end{cases}$$

-*Fertility Class (FC):* forest management unit distribution in fertility classes showed a reduced frequency in the most fertile classes. For this reason, this factor was normalised assigning value 1 to the first three classes, and a linear regression was applied for the classes from the fourth to the ninth, with decreasing values from 1 to 0:

$$FC_{\text{norm}} = \begin{cases} -\frac{1}{6}FC + \frac{3}{2}\text{ , for } FC > 3 \\ 1\text{ , for } 1 \leq FC \leq 3 \end{cases}$$

-*Productive Potential Index (PPI):* a linear regression was applied assigning increasing values from the lowest potential to the highest, in the range 0 to 1:

$$PPI_{\text{norm}} = \tfrac{1}{8}PPI - \tfrac{1}{8}.$$

Sixteen forest experts, including forest managers and Provincial Forest Service members, were interviewed to collect their personal opinion on the importance of the three factors previously described regarding forest management, with special attention on the topic of forest roads. In particular, a compilation of questions, based on a comparison of the three factors, was submitted to the experts by a personal interview. Following AHP concepts, personal opinions were implemented by *Expert Choice* ® software to obtain an impartial result on the importance of analysed factors for forest roads management. The software compared the answers given by people interviewed and provided the 'weight' value in % for each factor.

Finally, one raster file was calculated for each factor involved in the analysis. The *RNI* map was calculated by the weighted sum between GS_{norm}, FC_{norm} and PPI_{norm}:

$$RNI = w_{GS} \cdot GS_{\text{norm}} + w_{FC} \cdot FC_{\text{norm}} + w_{PPI} \cdot PPI_{\text{norm}},$$

where w_{GS}, w_{FC} and w_{PPI} were the weights obtained for *GS*, *FC* and *PPI*, respectively.

The result was a map of the Paneveggio forest in which each pixel was classified in relation to accessibility requirements. The Paneveggio forest was divided into four road needs classes:

-***LOW***: with $RNI < 0.25$;

-***MEDIUM***: with $0.25 \leq RNI < 0.50$;

-***HIGH***: with $0.50 \leq RNI < 0.75$;

-***VERY HIGH***: with $RNI \geq 0.75$.

5.3 RESULTS

5.3.1 Forest road network analysis

The first step of this study collected information regarding the state of the forest roads network. A shape file was created and the road network is represented in **Figure 5.1**. In the related database, all of the information collected and cited in Section 2.1 was recorded. The total length of roads network within the forest area (2,803 ha) was 37.1 km, corresponding to a density of 13.2 $m \cdot ha^{-1}$, while in the overall property (4,366 ha) there were 52.4 km of roads, with a density of 12 $m \cdot ha^{-1}$. According to the Italian classification, the majority of forest roads (69% of total, 36 km) were classified as ‘Road for tractor’, while 25% were ‘Secondary road for truck’ and only 6% were included in the category ‘Main road for truck’.

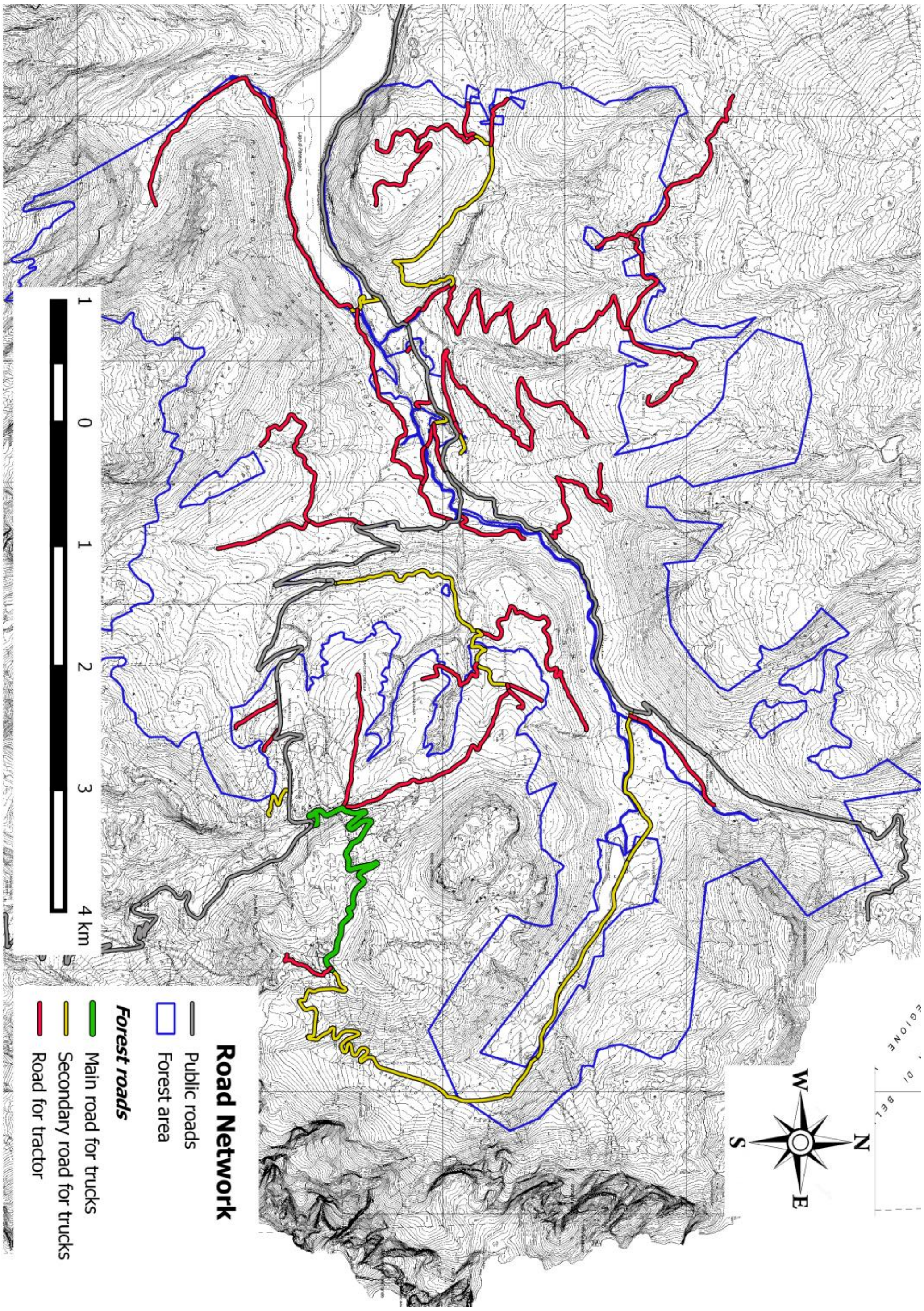

Figure 5.1. *Paneveggio forest roads network*

5.3.2 Accessibility analysis

The four methods described in Section 2.2 were implemented and compared. Results regarding the surface distribution between the three accessibility classes are reported in **Table 5.3**. A comparison between 'Method A' (**Figure 5.2**), 'Method B' (**Figure 5.3**) and 'Method C' (**Figure 5.4**), considering 'Method H' (**Figure 5.5**) as reference, was developed to evaluate the correspondence rate. In particular, the maps were overlapped and compared, identifying the percentage of pixels with the same accessibility class assigned (correspondence) and the others, where the model assigned different classes. The results showed that correspondences of 83.1%, 87.2% and 51.5% were calculated for methods A, B and C, respectively, using 'Method H' as the reference.

Table 5.3. *Surface distribution in the accessibility classes identified by means of the four analysed methods*

	SERVED		BARELY SERVED		NOT SERVED	
SURFACE	*%*	*ha*	*%*	*ha*	*%*	*ha*
METHOD H	56.2%	1574	20.0%	562	23.8%	667
METHOD A	54.7%	1534	21.2%	594	24.1%	675
METHOD B	60.2%	1689	21.4%	599	18.4%	515
METHOD C	26.8%	750	34.2%	960	39.0%	1093

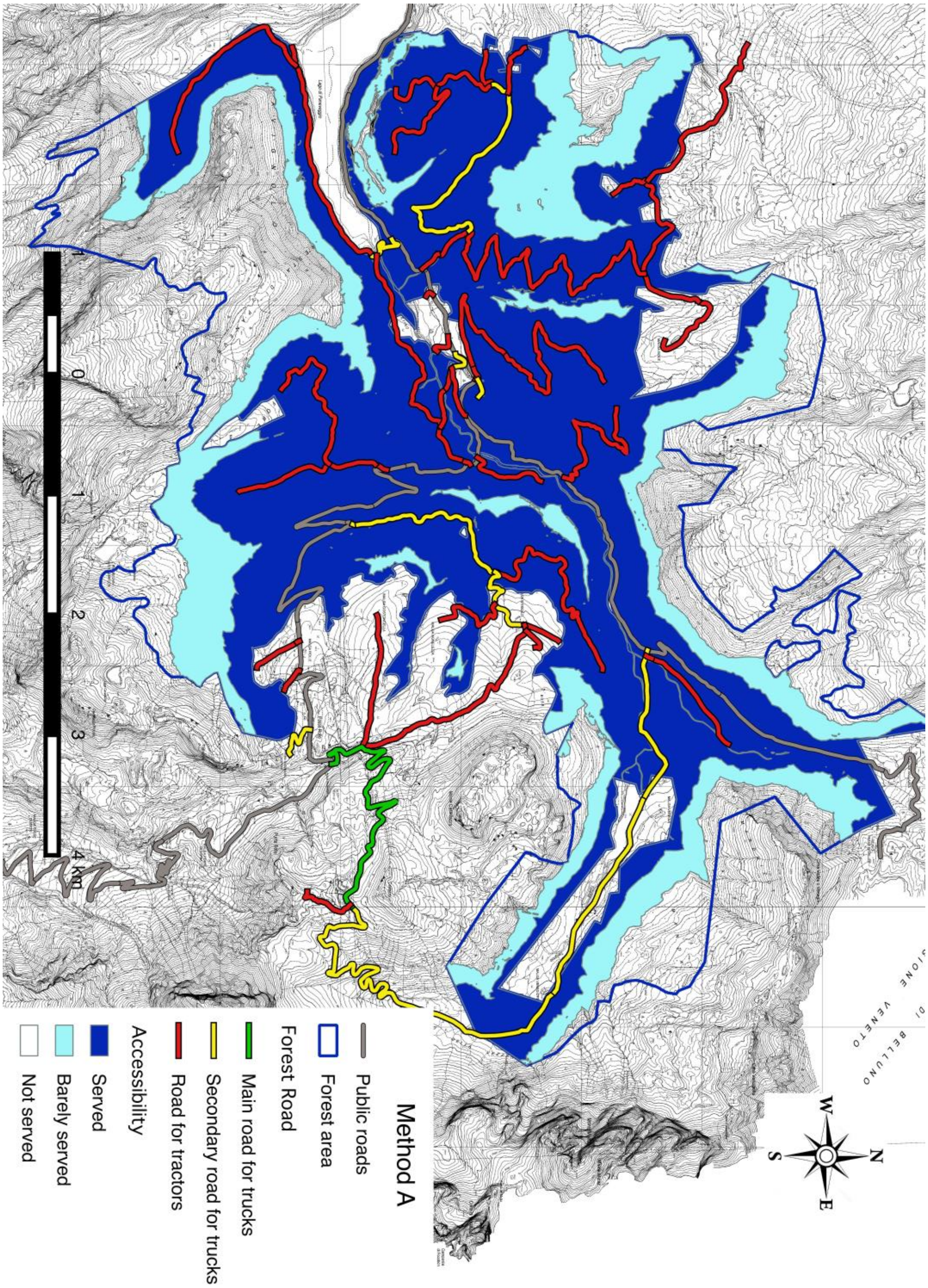

Figure 5.2. *Method A results, applied to Paneveggio forest*

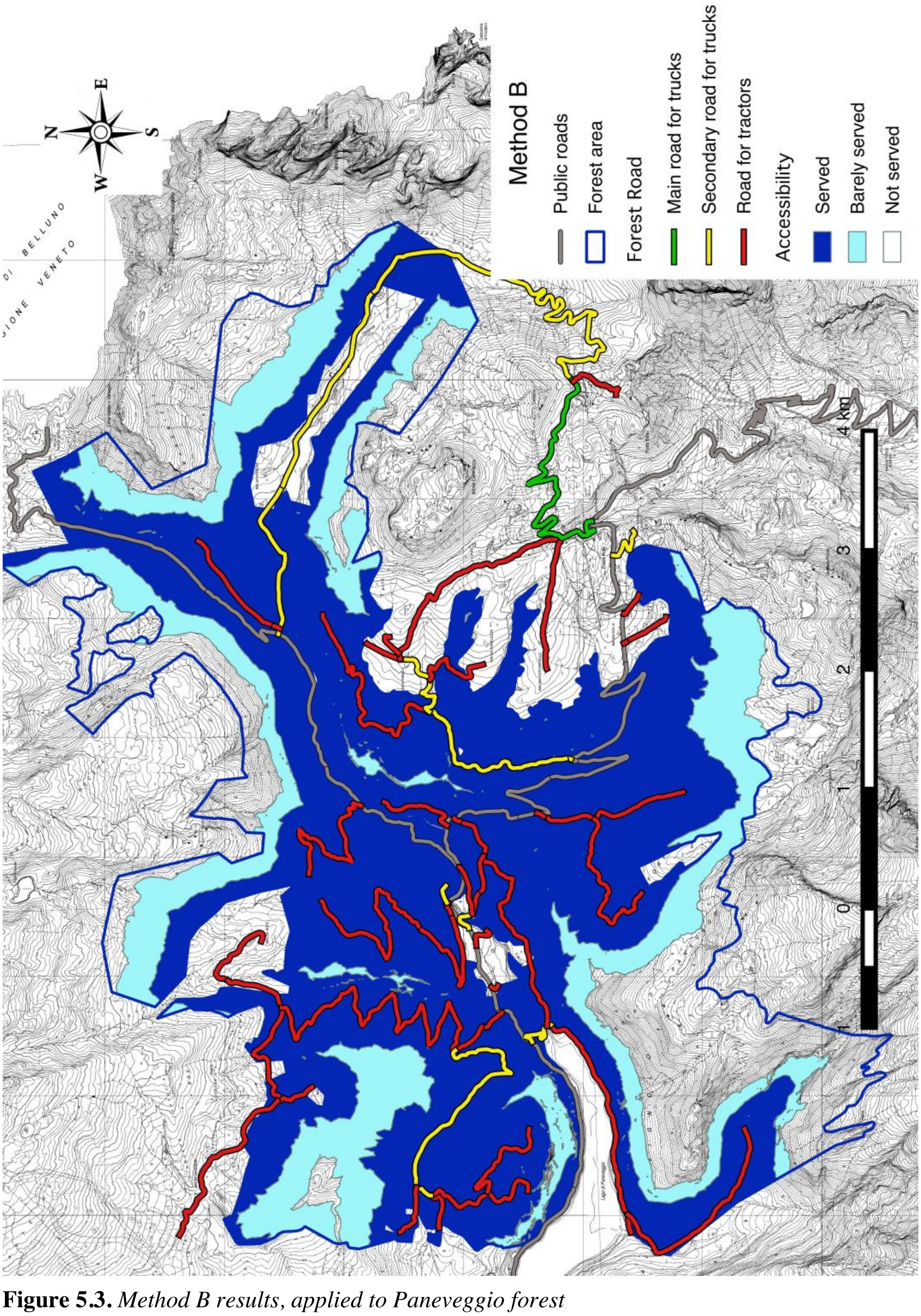

Figure 5.3. *Method B results, applied to Paneveggio forest*

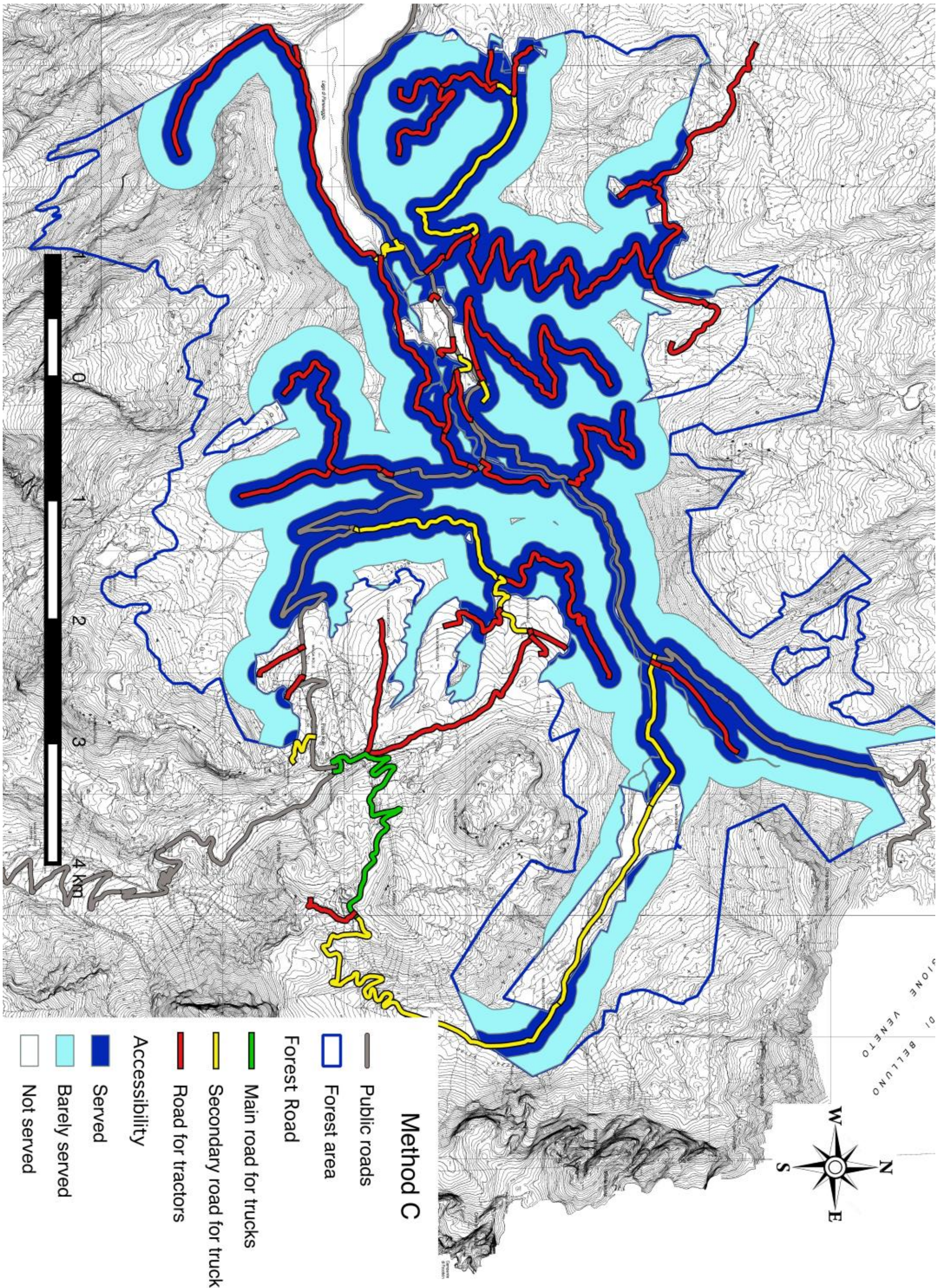

Figure 5.4. *Method C results, applied to Paneveggio forest*

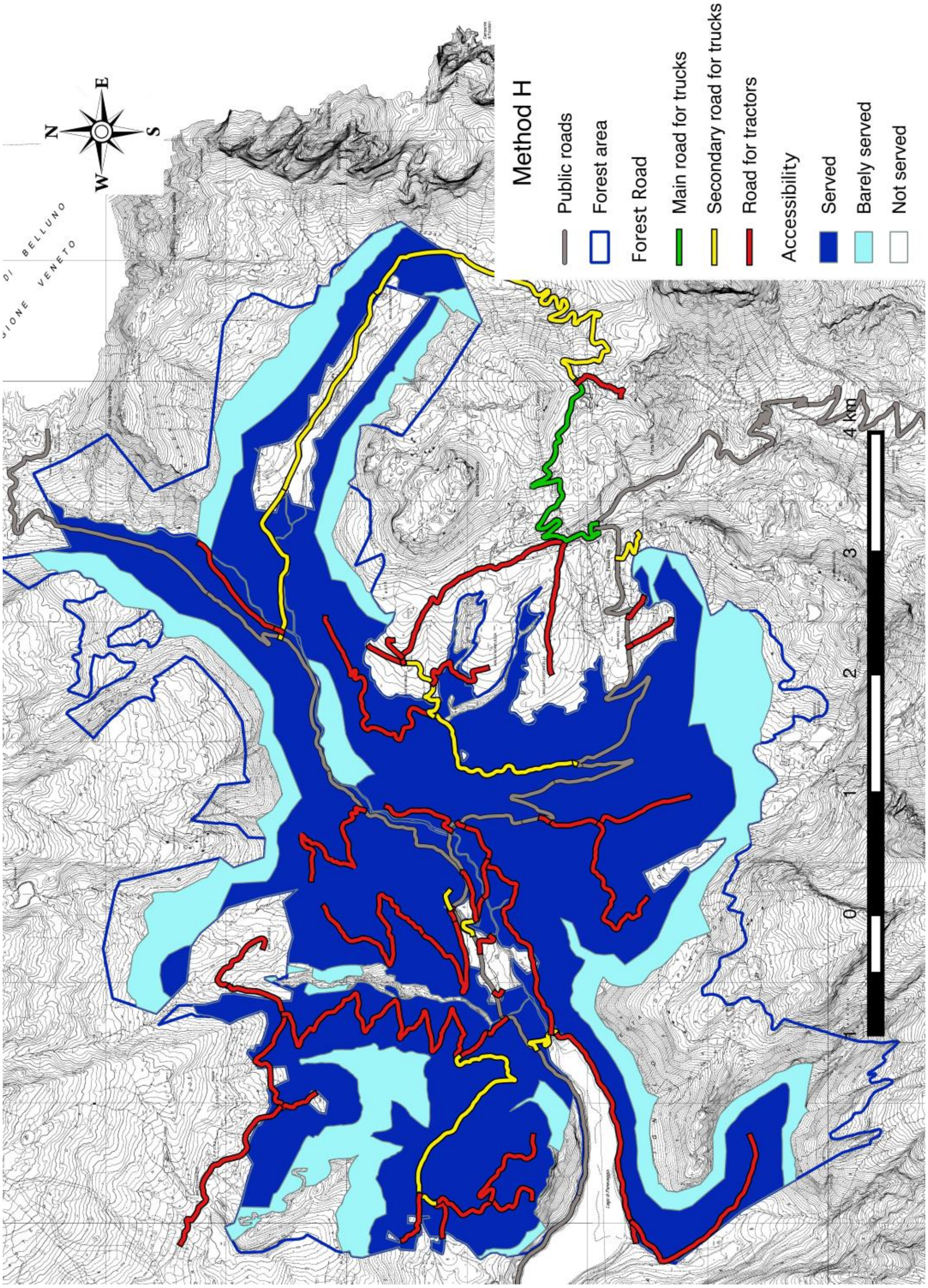

Figure 5.5. *Method H results, applied to Paneveggio forest*

5.3.3 Forest roads needs evaluation

The AHP results defined the values for the 'weights' to be used in the RNI calculation. In particular, the elaboration of experts' answers showed that the most important factor was the GS, with a weight of 45%, while weights of 30% and 25% were determined for FC and PPI, respectively. The final formula applied to each forest management unit in calculating the RNI was:

$$RNI = 0.45 \cdot GS_{\mathrm{norm}} + 0.30 \cdot FC_{\mathrm{norm}} + 0.25 \cdot PPI_{\mathrm{norm}}.$$

Summarized information on RNI distribution on the total surface, in relation also with the current accessibility results, is reported in **Table 5.4.**

Table 5.4. *Forest area distribution on the basis of RNI. For each RNI class, the distribution of the area in each of the current accessibility classes is shown.*

			TOTAL	*AT-PRESENT ACCESSIBILITY CLASS*		
				SERVED	*BARELY SERVED*	*NOT SERVED*
ROAD NEEDS INDEX	*LOW*	ha	75.7	0.0	22.4	53.3
		%	2.7	0.0	0.8	1.9
	MEDIUM	ha	765.2	185.0	238.3	341.9
		%	27.3	6.6	8.5	12.2
	HIGH	ha	1202.5	857.7	274.7	70.1
		%	42.9	30.6	9.8	2.5
	VERY HIGH	ha	759.6	644.7	64.5	50.4
		%	27.1	23.0	2.3	1.8

Figure 5.6 reports a graphical representation of the RNI results, distributed following the four classes established in Section 2.3.

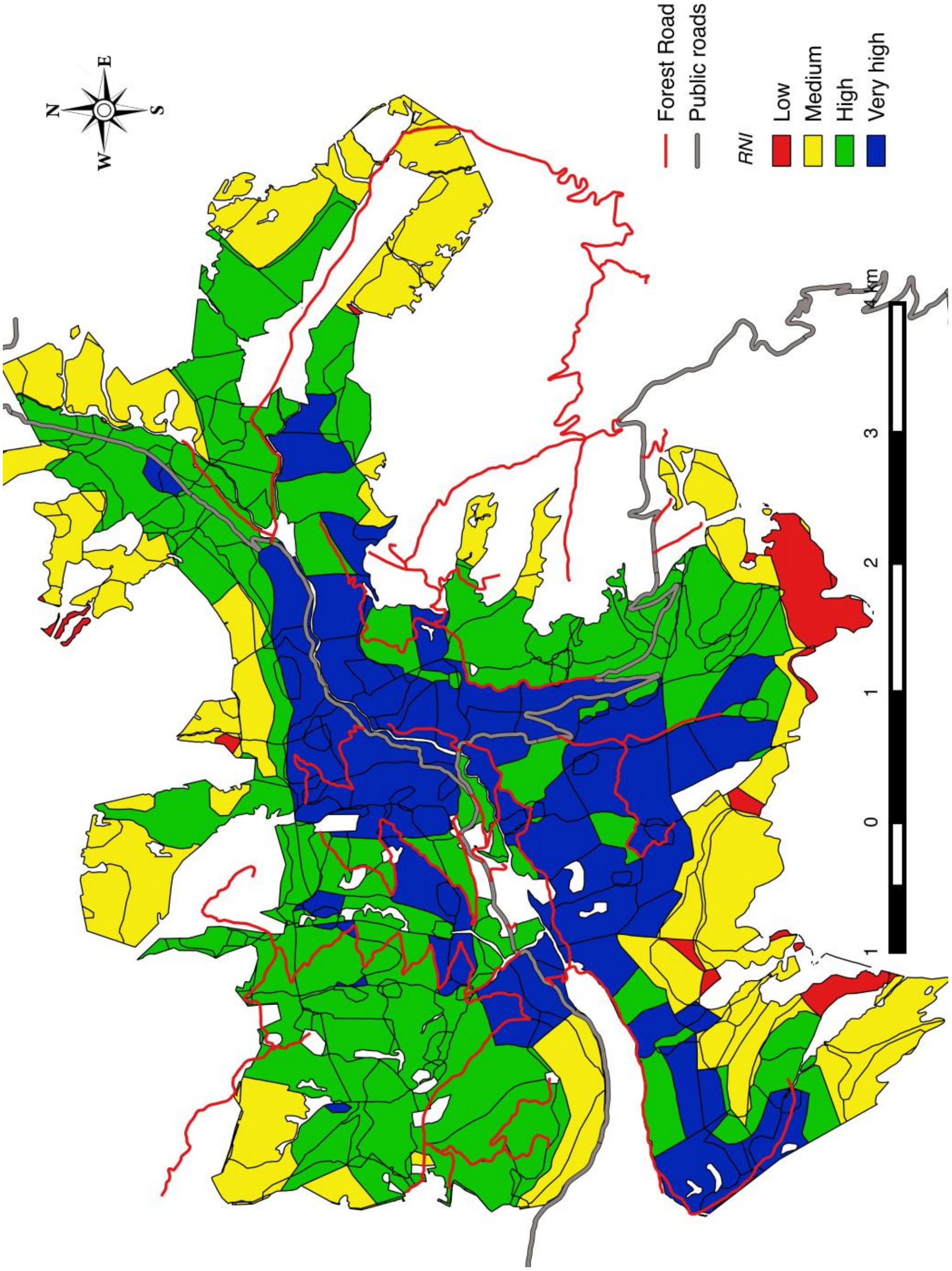

Figure 5.6. *Distribution of forest management units in classes depending on RNI*

Overall results were interpreted to identify the areas with criticism in terms of road accessibility. Taking into account all of the results, two new road branches were proposed. The two hypotheses are reported in **Figure 5.7.**

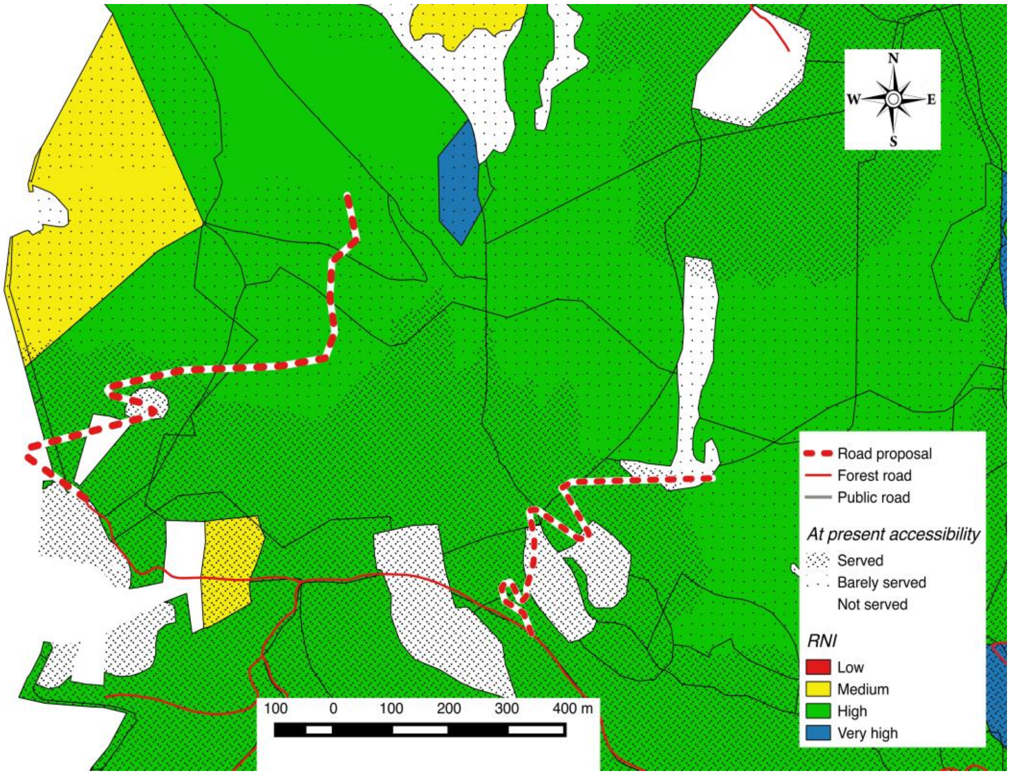

Figure 5.7. *Proposals for two new forest roads*

5.4 DISCUSSION

Because of the different analyses performed, different topics were investigated in this study and useful information was obtained to facilitate and improve the decision processes related to forest road network planning. Analysis of the existing road network highlighted the predominance (69%) of forest roads only suitable for the transit of tractor and trailer, while 25% were roads with better characteristics in terms of width, radius of curvatures and slope; only 6% of roads could allow the transit of heavy trucks. This information should suggest the enhancement of the main forest roads to improve and rationalise wood transport by means of heavy trucks instead of tractors and trailers. The slope is a crucial factor in accessibility estimation. In mountainous areas, the slope heavily influences the accessibility (Cavalli and Grigolato, 2009) and strongly affects the logging system and costs of forest operation (Hippoliti, 1997). In this study, the accessibility analysis added essential information regarding the rationality in forest roads distribution around the forest property. Comparing the applied methods, *Method C* showed the worst performance, in terms of correspondence, in comparison with results obtained by *Method H*, which was taken as the reference. *Methods A* and *B* had similar responses; *Method A* obtained better results than *Method B* considering the general surface percentage allocated to the three different categories, which were very similar in value to *Method H*. On the other hand, *Method B* showed better accuracy than *Method A*, considering the correspondence in pixel allocation. This similarity was expected, taking into account the similar approach used in the two methods. However, accuracy was considered as the main objective in identifying the best method for accessibility estimation, and *Method B* had the better performance in this sense. It showed a high rate of 'served' management units in Paneveggio forest (about 60% of the total) and a limited 'not served' area (18%). In this context, introducing the evaluation on the real needs of forest roads in the different areas, especially regarding barely and not served areas, could give an added value to the roads planning process according to the multi-criteria approach. As reported in Table 5.4, not served areas mainly referred to forest management units with a low or medium RNI, while only a limited area with high and very high needs was not served. Regarding 'barely served' management units, there was a reasonable rate of forest with 'medium' and 'high' RNI. In this case, an enhancement of the road network should improve accessibility conditions, optimizing productivity in forest operations. Regarding the three factors analysed in the AHP, technicians focused their main interest on growing stock (weight: 45%), which is a factor influencing short-term decisions. Fertility class had an intermediate weight (30%), thus highlighting the attention of forest technicians also on long-term aspects, while the productive potential index (25%) received a quite low weight. In practice, RNI analysis took into account a balanced mix of information aimed both to short- and long-term approaches for forest road network planning. However, the method could be improved through the implementation of more, or different, factors; in particular, the increments of volume should be considered–when available–to obtain a representative parameter related to stand productivity. Moreover, in RNI analysis, different solutions or alternatives could be implemented to optimize the methods depending on management priorities. In the case of special needs, specific factors could be introduced into the RNI calculation formula, enlarging the analysis to specific topics. An example of that would be the use of indicators regarding wildfire risk, or tourism points of interest. In these cases, the RNI analysis could give useful information in addition to the ordinary needs, normally satisfied when the road network is functional for forest operations.

5.5 CONCLUSION

In this study, a methodological approach aimed to improve forest road network planning, was developed and applied to a forest property. MCA and AHP criteria were applied by means of GIS, exploiting terrestrial information and forest characteristics. The state and accessibility requirements in a forest area have key roles in optimizing road network management. The analysis developed in this study could be a real added value for managers during planning. In particular, the examined methods facilitate objective forest road planning, which permits optimization of resources and avoids the building of a useless road and/or oversized road networks. Enhancement of the forest road network, through well-defined improvements, guarantees the correct management of the forest, allowing all of the forest services, such as wood production, hydrogeological protection, tourism use and habitat conservation. In practice, a well-planned and well-realised road network maximizes the efficiency of all forest activities, minimizing the costs, both economically and environmentally. The approach described and achieved in this study perfectly fit in this perspective, reporting fundamental information useful for sustainable maintenance and development of the forest road network.

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CHAPTER 6

Conclusion

In modern forest management, all the ecosystem services provided by forests to Society should be taken into account in order to preserve their function, allowing at the same time the use of wood as an important and renewable raw material. In this thesis four different analyses were carried out regarding different topics in the field of sustainable forest operation. Sustainability of forest operations is strictly connected with environmental, social and economic aspects. Results showed how the industrial processes related with wood transformation are the most relevant in the life cycle of a wood product as pellet, considering environmental impacts. Moreover, it was clear how the energy requirements mainly influenced the environmental profile of the product, and how the research of different solutions, aimed to the use of renewable resources for energy production, could reduce the impacts and could improve the environmental sustainability of a product. Moreover, wood extraction showed limited levels of emissions, but it was demonstrated that different choices regarding work systems in forest operation could influence the final environmental profile of the product. However, as in the analysed case study related with firewood production, not only emissions should be taken into account. In fact, the results identified SWS as better than WTH in all the impact categories examined, but a different level of mechanization was involved in the two systems. In SWS a higher number of working hours was required both in motor-manual processing by chainsaw and in manual loading of wood pieces on tractors during extraction. This could have negative effects in terms of work ergonomics and safety, due to the low mechanization level, which implies strenuous work. Regarding the analysed emissions, it was interesting the considerable contribution to total impacts derived from worker transportation to the work site, which should considered in Life Cycle Inventory as it happened in the most of LCA studies. Regarding safety and health of forest workers, the analysis of severity and frequency indexes developed in this work showed results that confirmed forest operations as one of the most dangerous work in all productive sectors. Forest workers are exposed to high-risk levels, especially in mountainous areas and applying limited levels of mechanization. For these reasons, improvement of work conditions should be based on mechanization, which generally guarantees better work conditions in terms of both work safety and ergonomics. In order to allow sustainable forest operation in a convenient environmental, social and economic way, a well-developed and well-organised management is fundamental. In this work, an essential phase, proper of forest management, has been studied. Forest road network planning has been analysed in deep in order to develop a DSS to improve the information available for decision-making processes. In fact, a well-planned and well-developed road network permit to have a useful and efficient infrastructure system. The optimization in terms of accessibility, focused on the areas were roads are required, permits to concentrate resources where necessary, avoiding the building of useless roads. Summarising, an efficient road network permits efficient forest operations minimizing the financial and environmental costs, and the risks for forest operators. The different analysis developed have demonstrated the wide interests related with forestry, which have to be taken into account following a sustainable perspective. Wood is surely a valid alternative to fossil fuels and a competitive material, e.g. for construction and furniture. However, wood ‘production’ is not totally lacking in emissions, and forest functions must be preserved and guaranteed for the future. For these reasons an integrated approach in forest management, which consider all the functions, interests and roles of the forests, is the best mean for maximizing the benefits for the Society and for maintaining the resource at the same or at a better level over time.

Finally, thanks to this work, several aspects were investigated, and several ideas emerged for further studies regarding the analysed topics and forest operations management in general. Regarding emissions and environmental impacts in forestry, LCA is an innovative and changing fast tool, with an ample room for improvement. A large interest on improving research could regard especially the consequences in ecosystem modifications. The estimation of soil emissions variation, carried out in the chapter regarding forest operations in coppices, showed an interesting field to be enhanced in order to better understand the real impacts related with wood harvesting. Moreover, the analysis of productive processes permits to identify the environmental, financial and social hotspots, allowing the study of new sustainable solutions. Each aspect analysed is fundamental in a sustainable approach; the reduction of emissions and related environmental impacts cannot get worse health and safety conditions to forest workers, and cannot became economically unsustainable. In conclusion, a holistic approach at sustainable forest operation, useful for highlighting connections and relative influences among all the factors and aspects involved, is recommended as the right way for determining and applying improved technical solutions.

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