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The eco-efficiency of forest operations in complex scenarios and the role of harvesting and transportation system on the carbon balance

PhD Program Coordinator: Prof. Marco Borga

Supervisor: Prof. Stefano Grigolato, Ph.D

Co-Supervisor: Dr. Omar Mologni, Ph.D

PhD candidate: Dr. Alberto Cadei

Summary

The interest in sustainable forest management has increased in recent decades. Sustainable forest management is a crucial element in reaching the ambitious climate-neutral goal of the European Union by 2050. Wood-based material and wood-based biofuel are the products that can be obtained by active forest lmanagement. Focusing on mountain forest management, the results of climate change are increasingly evident in terms of frequency and magnitude of biotic and abiotic disturbance. If, on one side, the challenge is to reduce the emissions of forest operation, on the other side is more frequent to operate in extraordinary conditions than before and salvage damaged trees after abiotic or biotic forest disturbance. New tools and technology are available to work in extraordinary conditions in mountain forest areas. Furthermore, propulsion systems based on electric or hybrid engines for forest operation machines have been produced. This thesis, based on a collection of six different scientific publications, focuses on the eco-efficiency analysis of forest operations under climate change scenarios, particularly in salvage logging operations after windthrow.

A state-of-the-art about windstorm impact on European forests was completed to give a general overview of cause-effect linkage after a windstorm. Focusing on salvage logging operations after Vaia storm in Italy, a case study was conducted to understand the relationship between ground slope and machine tilt when harvesting and extracting timber. Furthermore, productivity and energy efficiency analysis was carried out to better understand the effect of salvage logging on productivity and the role of new propulsion systems in reducing carbon emissions. Wood-chipping activities were considered to take into account all the operations related to salvage logging (harvesting and wood-chipping low-quality wood residues). The evaluation of fuel consumption of wood-chipping activities related to residual low-quality wood was performed according to the mountain road network and forest accessibility. Finally, automatic data collection methodology was applied to assess the efficiency of fully mechanized harvesting systems and evaluate the feasibility of long-term monitoring using machines' sensors.

Riassunto

L'interesse per la gestione forestale sostenibile è aumentato negli ultimi decenni. La gestione sostenibile delle foreste è un elemento cruciale per raggiungere l'ambizioso obiettivo di neutralità climatica dell'Unione Europea entro il 2050. I materiali a base di legno e i biocombustibili legnosi sono i prodotti che si possono ottenere da una gestione forestale attiva. Concentrandoci sulla gestione delle foreste montane, i risultati del cambiamento climatico sono sempre più evidenti in termini di frequenza e magnitudo dei disturbi biotici e abiotici. Se, da un lato, la sfida è quella di ridurre le emissioni delle operazioni forestali, dall'altro è più frequente operare in condizioni straordinarie rispetto al passato e recuperare gli alberi danneggiati a seguito di un disturbo abiotico o biotico forestale. Sono disponibili nuovi strumenti e tecnologie per lavorare in condizioni straordinarie e nelle aree forestali montane. Inoltre, sono stati realizzati sistemi di propulsione basati su motori elettrici o ibridi per le macchine specializzate per l'utilizzazione forestale. Questa tesi, basata su una raccolta di sei diverse pubblicazioni scientifiche, si concentra sull'analisi dell'eco-efficienza delle operazioni forestali in scenari di cambiamento climatico, in particolare nelle operazioni di recuero di legname danneggiato in seguito a schianti da vento (*salvage logging)*.

Inizialmente, è stato condotta una revisione dello stato dell'arte sull'impatto delle tempeste di vento sulle foreste europee per fornire una panoramica generale del collegamento causa-effetto a seguito di una tempesta di vento. Concentrandosi sulle operazioni di *salvage logging* dopo la tempesta Vaia in Italia, è stato condotta un'analisi per comprendere la relazione tra la pendenza del terreno e l'inclinazione delle macchine forestali durante il taglio e l'esbosco del legname. Inoltre, è stata condotta un'analisi della produttività e dell'efficienza energetica per comprendere meglio l'effetto delle operazioni di *salvage logging* sulla produttività e il ruolo dei nuovi sistemi di propulsione nella riduzione delle emissioni carboniche. Le attività di cippatura sono state considerate per tenere conto di tutte le operazioni legate al *salvage logging* (utilizzazione forestale principale e valorizzazione energetica dei residui legnosi di bassa qualità). Una valutazione del consumo di combustibile delle attività di cippatura del legno di bassa qualità è stata effettuata in base alla rete stradale e all'accessibilità forestale. Infine, è stata applicata una metodologia di raccolta automatica dei dati per valutare l'efficienza dei sistemi di utilizzazione completamente meccanizzati e valutarne la fattibilità del monitoraggio a lungo termine utilizzando i sensori delle macchine forestali.

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These three years of PhD were exciting and allowed me to grow from a personal and professional point of view. I have to recognize several people who help me in many different ways.

Prof. Stefano Grigolato and Dr. Omar Mologni, my supervisor and co-supervisor, respectively, they spur me during these years and have always maintained a stimulating work environment open to discussions and collaboration since my master's degree thesis.

Prof. Bruce Talbot from the University of Stellenbosch maintained a friendly and peaceful environment during my period in South Africa, sharing his competence and knowledge and allowing me to work also in contact with contractors and sawmills.

Even if he is not directly involved in my research project, Prof. Raffaele Cavalli always gives me his feedback and represents an example of professionalism.

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1 Introduction

Natural sources are considered limited and finite. Considering the increasing economic development and population growth, the global economy will drive to material consumption. Therefore, the increase of the demand for natural sources is considered one of the major causes of biodiversity loss, ecosystem degradation, social inequality and other negative externalities (FAO, 2022). A sustainable economy aims to increase the efficiency and sustainability of the use of natural and renewable sources, taking into account the limits of planet sources (European Commission, 2018). Among the different ecosystems that can provide raw materials, forests are considered one of the most important (Rist and Moen, 2013).

Forest ecosystems, in particular, provide essential services for the population, such as raw material (wood, biofuel) but also purify water and air, regulate the climate, and recycle nutrients (Apsalyamova et al., 2015; Eurostat, 2020). As defined by European Environment Agency (EEA): "*Sustainable management means the stewardship and use of forests and forest lands in such a way, and at a rate, that maintain their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems*".

Wood is considered one of the world's most important renewable raw materials. Wood-based products are used in new emerging markets (chemical and textiles sectors) as well as in traditional markets (wood construction, pulpwood, paper wood and energy wood) (FAO, 2022). As reported in the EUROSTAT statistics report (Eurostat, 2020), in 2020, 180 million hectares of forest covered the EU, and 10.3% of the total manufacturing sector employment was the wood-based industry that generated 138.6 billion € in 2018. As a product chain, the input to the downstream wood-based industry comes from forestry and logging activities that generated 26.2 billion € in 2017 in the EU countries. Therefore, wood harvesting and derived wood product play a crucial role from the economic point of view of the EU countries, but the efficiency of the forest chain is a key element that enables the sustainability of the entire chain (Ottaviani Aalmo et al., 2021).

To increase the environmental sustainability of the forest sector, a comprehensive analysis of the input factors (e.g., energy) and output generated (e.g., wood-based products) needs to be carried out. Even though wood-based raw materials (wood and wood-based biofuel) are well known as products able to store a large quantity of carbon, the emission related to the forest operation and transportation system needs to be evaluated considering the input resources (energy) and the output produced (wood). To optimise the use of wood-based products, the cascade use was proposed to effectively use, first of all, wood for higher-add values products (such as round wood) and only at the end the low-quality wood (such as top and branches) for energy purposes (Bais-Moleman et al., 2018).

1.1 Forest operations under climate change scenarios

The future perspective of the forest is focused on long-term strategic management for a prosperous, competitive, climate-neutral economy. In recent decades, natural disturbances (biotic and abiotic) have seriously damaged world forests (Lindner et al., 2010). Moreover, the effect of climate change and global heating reflects on natural disturbances events, particularly in terms of frequency of severity higher than before (Seidl et al., 2014).

Focussing on European forest, windstorms are currently one of the major disturbance factors (Gardiner et al., 2013), which averages two catastrophic storms a year (Motta et al., 2018), followed by bark beetle outbreaks after one or two years. In fact, the high quantity of damaged trees can lead to an increased risk of wildfires and outbreaks of forest pathologies and insects (in particular, *Ips typographus L.* on *Picea abies*) (Gardiner et al., 2013). In the past six decades, windstorms have damaged standing forest which, on a yearly average, equals to about 38 million m^3. The effects of windstorms on forests have been documented in literature mainly for central and northern Europe (Gardiner et al., 2013). In 1966, the Eastern Alps were affected by a storm which have damaged about 0.7 million m^3 of timber in Trentino Province (Italy), in addition to 1.3 million m^3 of timber in Austria.

Moreover, in the early 1990s, the "Vivian" storm damaged more than 60 million m^3 of timber in Switzerland. "Lothar" and "Martin" storms hit France, Germany and Belgium in the late 1990s and damaged 240 million m^3. In 2005 the storm "Gudrun" struck northern Europe, damaging 75 million m^3 of timber. Two years after, the storm "Kyril" damaged over 66 million m^3 of timber in many European countries, such as Ireland, France, Belgium, Holland, Denmark, Sweden, Austria, and Germany. The latest event in chronological order, as well as the most significant recorded in Italy, occurred with the "Vaia" storm, which affected the north-eastern sector of the Italian Alpine arc in October 2018.

Seidl (2014) estimated that on average, considering the forest management constant, in the period 2021-2030, the wind damage will be about 44 million m^3 per year (+ 229.4% compared with the period 1971-1980). Other authors also indicate that the actual severity of storms in the wake of climatic changes may increase during the following decades (Gardiner et al., 2013a). The main consequences of these strong windthrows are the partial or total loss of the functions of the forest, including the protective function in steep terrain. In these areas, forest operations with the purpose of completely or partially removing the damaged trees, also called salvage logging, must be characterised by environmental and ecological sustainability, as well as aimed at optimising the interventions economically to reduce the loss of value of the timber (Hlásny et al., 2019).

The critical aspects to be addressed in salvage logging are different from ordinary logging operation conditions (e.g, selective cut, clear cut), with an increment of the safety risk for the forest operators (Sullman and Kirk, 2001). Furthermore, as in the case of the Vaia storm in the Eastern Alps, the high presence of damaged wood in steep and rough terrain determines complex conditions. Nevertheless, if carried out quickly, salvage logging can reduce the economic loss of dead or damaged timber and reduce the risks associated with bark beetle outbreaks in coniferous stands in neighbouring stands (Thorn et al., 2014). In any case, salvage logging is not the solution everywhere. In fact, post-windstorm management needs to be planned in a meticulous and priority manner analysing through a qualitative and quantitative analysis the areas concerned, providing for rapid and priority interventions based on the functions such as direct protection (rockfall, landslides and avalanches), water basin management and biodiversity conservation (Lindenmayer and Noss, 2006).

As a consequence, the logging operations must be planned and regulated with prescriptions and according to the existing road network (both forest and public roads) also in terms of qualitative and quantitative standards (load capacity, curve radius, carriageway width, vertical alignment, surface type, storage area and eventually damage due to the storm) (Enache et al., 2016). The previous consideration assumes a higher value in the case of windthrow involving huge quantities to be extracted in extraordinary conditions such as very steep and rough terrain and in the case of a low-density forest road network as well a public road network with strong limitations in terms of heavy truck traffic (Grigolato et al., 2013). The complex conditions require highly specialised operators and machines to apply special logging techniques and procedures and can negative affect productivity and logging costs.

The productivity of salvage logging operations is lower compared to ordinary situations both in the case of the motor-manual system based on operators with chainsaw and the use of forest tractors as well in the case of fully mechanised operations with harvester and forwarder (Enache and Stampfer, 2014). In a recent study in the Baltic area, it has been highlighted that the harvester and its components are more stressed when they work in salvage logging operations. Consequently, the intervention's cost will also be 10-30% higher than in ordinary situations, with productivity reduced by up to 33% compared to ordinary conditions (Kärhä et al., 2018). The operator's experience is a fundamental element that is considered one of the main factors affecting productivity and, consequently, costs. In fact, if the harvester operator has little experience, the difference in costs between ordinary and extraordinary interventions rises, reaching a maximum increase of 70% (Purfürst and Erler, 2011).

1.2 Harvesting methods and systems in forest operations

The forest harvesting method is classified based on the timber form used to deliver the trees to the roadside, while the harvesting system is defined as the tools and equipment used to harvest standing trees inside a forest (Längin et al., 2010). Depending on i) terrain slope, ii) extraction distance, and iii) ground's load-bearing capacity, harvesting systems can be classified as a)ground-based, b) cable-based, or c) aerial-based harvesting systems (Figure 1.1).

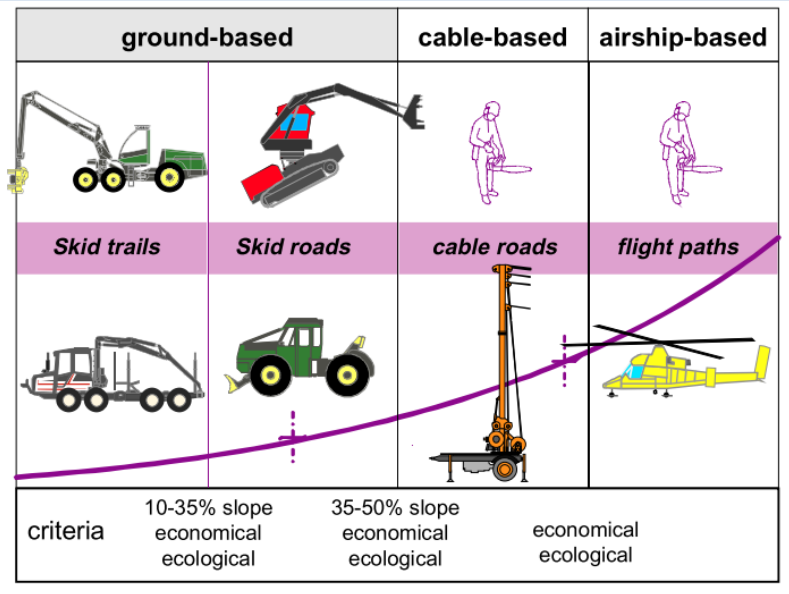

Figure 1.1- *Simplified scheme on the technical-economic feasibility of the main utilisation systems concerning the slope of the land, roughness, load-bearing capacity and distance of extraction (retrived from Heinimann, 2004)*

The "Cut-To-Lenght" (CTL) method consists of felling and processing the trees at the stump area and, in a second phase, transport the logs outside the stand to the landing or road side. The CTL can be semi-mechanised based on chainsaw operators for the felling and processing and transportation by skidder or tractor and trailer. The CTL method is very common in the fully mechanised system using two specialised machines: the harvester (used for felling and processing) and forwarder (used for log transportation). The "Full-Tree" (FT) method consists of felling the tree and extracting the whole tree (e.g., skidder) to the forest road or landing where the same tree is delimbed and cut mechanically or through a chainsaw operator (Visser and Stampfer, 2015).

Harvesting systems are classified as: Ground-based, Cable-based and Aerial-based harvesting systems. Ground-based systems use terrestrial machines to perform felling, delimbing, bucking and extraction operations. Cable-based systems are characterised by rope-way systems where trees are delivered from harvesting areas to landing areas or road side (Saunders, 2006). Cable yarding is a typical system used for logging in steep and roughness terrain (Magagnotti et al., 2013; Mologni et al., 2019; Proto et al., 2016a). The aerial-based system used helicopters for yarding the wood from the forest to the landing area. Considering the high costs of helicopter operations, the aerial-based system is limited to sites with poor accessibility, high slope and roughness, where the use of other logging systems is complex and where the high-value timber justifies the costs. In some European countries, such as Switzerland and Austria, the aerial system is also extensively used for ordinary logging operations and not only in complex situations (Manzone and Balsari, 2017).

In the last decades, the increase in the level of mechanization has driven to the use of more powerful and heavy machines (Cambi et al., 2015), aiming to improve the efficiency of forest operations and reduce the risk for forest operators. The high costs and risks to the operators' safety in using cable-based systems on steep slopes terrain permitted to expand knowledge and research to identify more efficient and safe systems for use on steep slopes terrain (Mologni et al., 2016). In cable-based systems, considerable time is required for rigging the cable before extraction (Holzfeind et al., 2018). Therefore, thinning operations with cable yarders are often too expensive and, in many cases, omitted.

The adoption of highly mechanised work systems mainly concerns ground-based systems in which the operators are not in direct contact with the wood, but operate from a machines' cab by using self-propelled machines. Highly mechanised ground-based systems, compared with cable-based, in salvage logging, increase the operators' safety (Sullman and Kirk, 2001a), guaranteeing high productivity of the system.

1.2.1 Forest operations in steep terrain

In complex terrain and mountain areas, characterized by a low density of forest road network, the use of fully mechanised systems in salvage logging operations is difficult. In these conditions, the primary system remains the semi-mechanised system based on motor-manual felling with a chainsaw and timber extraction by cable yarders or skidders (Bodaghi et al., 2018).

In recent years, even the fully mechanised system based on the combined use of harvesters and forwarders has been spreading with heavier and more suitable machines for working on steep and trafficable terrain (Mologni et al., 2016; Visser and Stampfer, 2015). In those machines, the increase of weight and technology increase both stability and ergonomics with self-levelling and rotating cabins (Cavalli and Amishev, 2019; Phairah et al., 2016). In addition, mechanical implementation (e.g., independently suspended tracks, wheels mounted on hydraulically driven arms, synchronised winch) aiming to improve traction expanding ground-based harvesting systems into complex and steep terrain up to 75%–85% slope (Visser and Stampfer, 2015) (Figure 1.2). The operating limits shown in Figure 1.3 can be presented more in detail based on the specific characteristics of the machines used and the technology they are equipped with.

a)

b)

Figure 1.2 *- Example of winch-assist forwarder working in steep terrain (a) and harvester with balanced bogie and hydraulic pendulum arms and axles equipped with a hydraulic cylinders (b)*

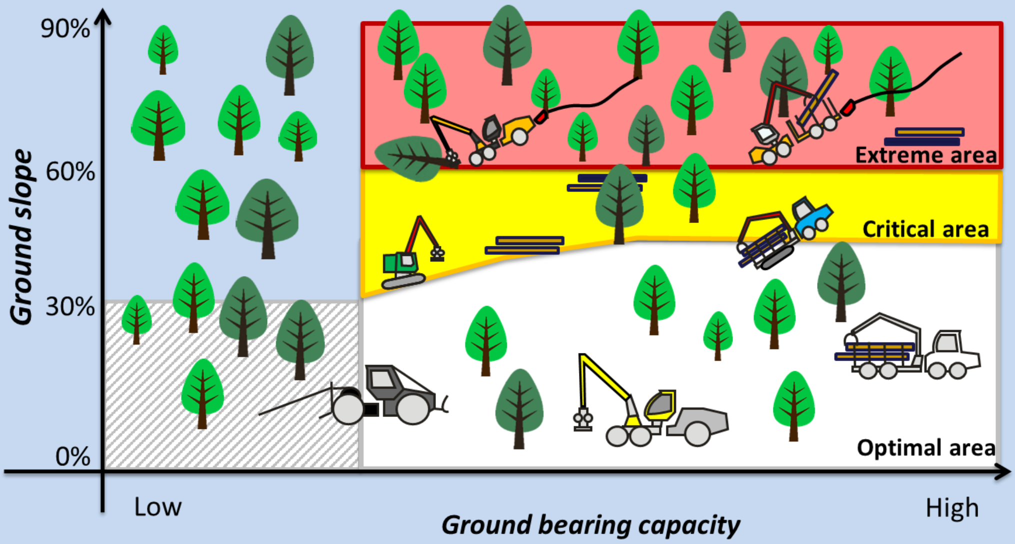

Figure 1.3 *- Operational limits of highly mechanised harvesting systems (elaborated by Prof. Stefano Griglato)*

Eco-Efficiency

The concept of eco-efficiency combines a specific system's economic and environmental performance (Koskela, 2015). Sorvari et al. (2009), reported a generic definition for eco-efficient activities: "*creating more value with fewer resources and less negative impact*". The primary means to increase eco-efficiency include reducing energy use per output unit. The objectives of minimum costs and minimum environmental impacts are, to a certain degree, not in conflict with each other.

In the forest sector, among the many wood-based products that can be provided by forest (e.g., sawlog, pulpwood, biomass, biofuels and bioenergy created from wood), the final aim is to reduce environmental impacts per unit of wood produced (volume or tonnes) with fossil-based fuels as the energy used (i). One of the environmental impacts studied is global warming potential, measured in CO_2-equivalent (CO_{2eq}) of greenhouse gas (GHG) emissions, and fossil energy demand, measured in megajoules (MJ). For example, increased use of machinery in harvesting practices, compared to traditional motor manual harvesting, increases fuel consumption and CO_2 emissions (Ackerman et al., 2017; Proto et al., 2017; Schweier et al., 2019).

One of the solutions to reduce the impact related to emission per unit of wood extracted is to optimize the machines' productivity with the same fuel consumption level. As shown by Spinelli et al. (2013), greater productivity has been found to optimise fuel consumption in harvesting operations. However, productivity must be monitored and understood to improve the operational efficiency of harvesting systems (Arlinger et al., 2010; Labelle et al., 2016; Olivera et al., 2016; Proto et al., 2018). Thus, the development and refinement of work productivity models for fully mechanised operations have been a standard procedure in forest operations for decades (Eriksson and Lindroos, 2014; Labelle et al., 2016; Visser and Spinelli, 2012).

While the increase of machines' productivity at the same fuel consumption rates can lead to a reduction of CO_2 emissions, alternative fuels and different propulsion systems have been proposed to perform low-emission or zero-emission vehicles (Daziano and Chiew, 2012). Hybridisation or electrification of propulsion systems used in forest operations is another solution that is available both for ground-based harvesting systems (Karlušić et al., 2020; Rong-Feng et al., 2017) as well as for cable-based harvesting systems (Cadei et al., 2021; Varch et al., 2020; Visser, 2015)

1.2.2 Methodologies used to detect eco-efficiency parameters

In order to understand and predict eco-efficiency, accurate predictions of the productivity and emissions of logging operations are required. Predictions are generally based on empirical data, but the amount of data and the methodology used to acquire the information vary greatly, depending on the precision required and the available resources. Commonly applied methods to assess performance in forestry include, for instance, time and motion studies (work observation) and follow-up studies (historical output records).

In time and motion studies, the productivity of a given observational unit is measured over a relatively short time (Björheden, 1991; Björheden et al., 1995). In contrast, follow-up studies rely on data gathered during normal production activities using forest companies' information systems, enabling the acquisition of large datasets (Manner et al., 2016; Rossit et al., 2019), using methodologies ranging from study-specific data collection to existing records collected as part of a company's everyday follow-up routines. Moreover, ideally, the follow-up studies should not interfere with routine work, leading to a reduction of the Hawthorne effect (i.e., changing in the individuals performance during the monitoring period). In addition, short-time studies are affected by the ground condition, machines, operator and generalization is usually not representative of a wide range of conditions (Eriksson and Lindroos, 2014; Proto et al., 2018)

There are lots of array of models for predicting the productivity of CTL machinery in both thinning and final felling operations (Brewer et al., 2018; Cadei et al., 2020; Eriksson and Lindroos, 2014; Gerasimov et al., 2012; Lindroos et al., 2017; Malinen et al., 2018; Nurminen et al., 2006; Proto et al., 2018). However, even if higher levels of detail and accuracy typically characterize the predictive models based on short time periods, the limited number of work samples reduces the possibility of expanding the model's application to other site conditions and operators.

The modern computerisation of specialized harvesting machines used in CTL method (e.g., harvester and forwarder) makes it possible to collect data automatically using the machines' controller area network (CAN Bus) and standard for forest data and communication (StanForD 2010) (Figure 1.4).

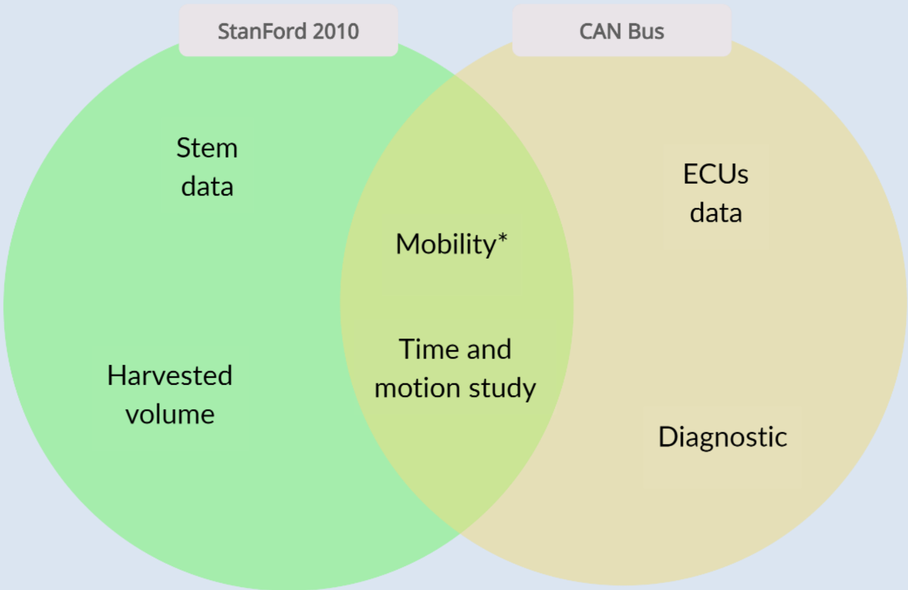

Figure 1.4 *- StanForD 2010 and CAN Bus data (*mobility parameter is available only if machine is provided by GNSS antenna)*

CAN Bus system is a system used to connect a machine's electronic control units (ECUs). The ECUs represent the system nodes that send messages through the CAN Bus network. The messages are composed of bit information. Typically, the standard CAN message frame, used for automotive and industrial applications is composed of 11-bit identifier (CAN 2.0A). However, for off-road vehicles a specific standard, SAE J1939, was developed for higher layer protocol using 29-bit message identifier (11-bit base identifier and 18-bit identifier extension) (Voss, 2008). In the case of the J1939, the 29-bit identifier contains the source information and, sometimes, the destination of the message insed the network. Therefore, to access at the CAN Bus network of an off-road machine specific plug and datalogger are needed. In addition, a database containing identifiers, names, numbers, and formats is necessary to decode CAN Bus messages. Used primarily by the automotive industry, vector database files (.dbc) have since become the de facto standard for exchanging CAN descriptions. CAN Logger is a control unit that filters and memorises all CAN frames of the bus on which is connected. Besides the system, the data logger can directly be interfaced to a PC through USB and convert the raw message sniffed to comprehensible messages (Marx, 2015).

StanForD is one of the most widely used communication systems by forest machine manufacturers and it is used in order to measure the quantitative and qualitative parameters of the CTL method (Arlinger et al., 2010). The version of StanForD before 2010 derives the harvester productivity in an aggregate way, with a daily detail level (Strandgard et al., 2013). StanForD 2010 uses the XML format, an open and general format that is used in many applications where data needs to be stored and communicated. This can help avoiding unnecessary conversion between formats in communication with different data management systems. For software developers, XML has the major advantage of having many complete and freely available solutions for reading and managing XML files, which saves time and development resources. In addition, files can easily be checked against the XML Schema to ensure that they comply with the standard. Even if XML files are large, they are easy to compress with zip compression, which saves space and requires less transfer capacity. Few studies have tested or validated the automatic acquisition of data using On Board Computer (OBC) by comparing the machine derived productivity models to models developed using traditional time study methods. Strandgard et al. (2013) calculated and modelled productivity using StanForD stem (*.stm) files by using the difference between consecutive harvest time stamps to determine cycle length. According to Strandgard et al. (2013) when compared with productivity models produced from time study data on the same set of trees and using consistent individual stem volume measures for the two datasets, no significant differences were found suggesting that productivity could be accurately modelled using data from StanForD stem files.

1.3 Thesis aims and structure

Considering the available technology and the different harvesting system, the present thesis aims to evaluate the eco-efficiency of harvesting systems and transportation considering the effect on carbon balance related to salvage logging operations in steep terrain. The present thesis is structured as a collection of scientific publications. This thesis is based on six different scientific publications; each chapter is based on a single scientific publication (Figure 1.5).

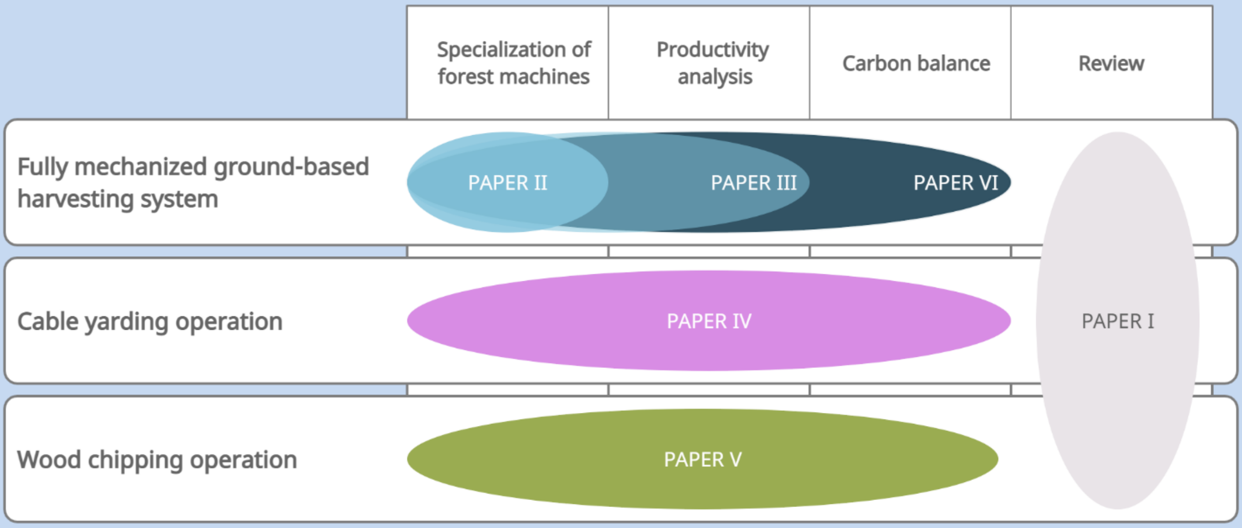

Figure 1.5 *- Conceptualisation of the thesis divided per article topic*

The thesis's specific objectives are to evaluate windthrow's effect in forest operations, starting from a wide perspective of the European forest (Paper I). Given the results from the review, Vaia storm will be considered for analysing the effect of windstorm on forest operations in Italy. The use of specialized forest machines in steep terrain and salvage logging operations will be analysed to evaluate the effect of ground slope on machine tilt (Paper II). In addition, considering the impact of windthrow on forest operations, the efficiency of forest operations in salvage logging and wood chipping operations will be assessed (Paper III, Paper V) and the efficiency of new propulsion system to reduce the impact of timber harvesting operations will be evaluated (Paper IV). Finally, considering the availability of different technologies to carry out automatic data collection, the last article will explain the advantage of commercial platforms to evaluate the efficiency (Paper VI).

Different sensors and methodologies are considered to evaluate the efficiency of harvesting and wood-chipping activities (Figure 1.6). The data collection methods include:

- manual data collection with external sensors attached to the machine (e.g, video cameras, accelerometer, GNSS sensors) or direct measurement (e.g, refuelling, log volume and diameter);
- automatic data collection using forest machine system (e.g., StanForD, CAN Bus).

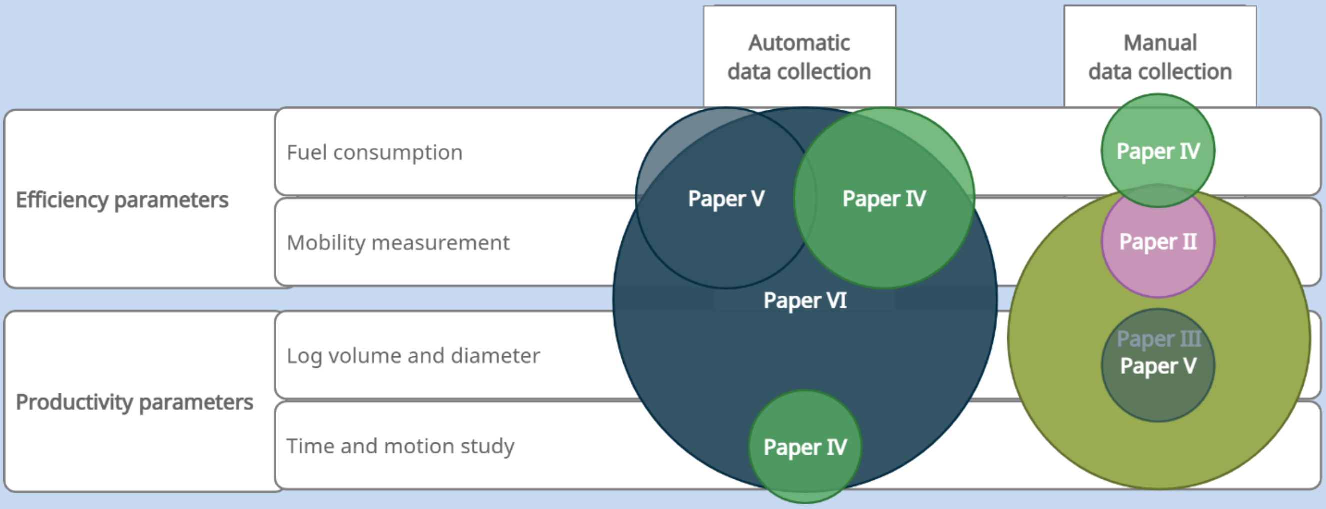

Figure 1.6 *- Conceptualisation of the thesis divided per methodology used in the different article*

1.4 List of publications

This thesis is based on the following scientific publications:

I. [Submitted] Romagnoli, F*., **Cadei, A**., Costa, M., Marangon, D., Nardi, D., Pellegrini, G., Masiero, M., Secco, L., Grigolato, S., Lingua, E., Picco, S., Pirotti, F., Cavalli, R (2022). Analysis of windstorm impacts on European forest-related systems: a transdisciplinary perspective, Forest Ecology Management

II. **Cadei, A***., Mologni, O., Proto, A.R., D'anna, G., Grigolato, S., 2020. Using high-frequency accelerometer to detect machine tilt, in: 19th International Scientific Conference Engineering for Rural Development Proceedings. Latvia, p. 7. https://doi.org/10.22616/erdev.2020.19.tf512

III. **Cadei, A**., Mologni, O., Röser, D., Cavalli, R., Grigolato, S*., 2020. Forwarder Productivity in Salvage Logging Operations in Difficult Terrain. Forest. 2020 11, 14. https://doi.org/10.3390/F11030341

IV. **Cadei, A***., Mologni, O., Marchi, L., Sforza, F., Röser, D., Cavalli, R., 2021. Energy efficiency of a hybrid cable yarding system: A case study in the North-Eastern Italian Alps under real working conditions. Journal of Agriculture Engineering. 52, 10. https://doi.org/10.4081/jae.2021.1185

V. **Cadei, A***., Marchi, L., Mologni, O., Cavalli, R., Grigolato, S., 2021. Evaluation of wood chipping efficiency through long-term monitoring, in: Lo Monaco, A., Macinnis-Ng, C., Rajora, O.P. (Eds.), Environmental Sciences Proceedings. MDPI AG, p. 7. https://doi.org/10.3390/IECF2020-08078

VI. Bacescu, N. M., **Cadei, A**.*, Moskalik, T., Wiśniewski, M., Talbot, B., Grigolato, S.. 2022. Efficiency Assessment of Fully Mechanized Harvesting System through the Use of Fleet Management System. Sustainability 14:16751. https://doi.org/10.3390/su142416751

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2 Paper I - Analysis of windstorm impacts on European forest-related systems: an interdisciplinary perspective

Federica Romagnoli [a*], Alberto Cadei [a], Maximiliano Costa [a], Davide Marangon [a], Giacomo Pellegrini [a], Davide Nardi [b], Mauro Masiero [a], Laura Secco [a], Stefano Grigolato [a], Emanuele Lingua [a], Lorenzo Picco [a], Francesco Pirotti [a], Andrea Battisti [b], Tommaso Locatelli [c], Kristina Blennow [d,e], Barry Gardiner [f,g], Raffaele Cavalli [a]

[a] Department of Land, Environment, Agriculture and Forestry (TESAF), University of Padova, Viale dell'Università 16, 35020 Legnaro, PD, Italy;
[b] Department of Agronomy, Food, Natural resources, Animals and Environment (DAFNAE), University of Padova,35020 Legnaro, PD, Italy;
[c] Nothern Research Station (NRS), Roslin EH25 9SY, Scotland
[d] Department of Landscape Architecture, Planning and Management, Swedish University of Agricultural Sciences, P.O. Box 190, SE-234 22 Lomma, Sweden
[e] Department of Physical Geography and Ecosystem Science, Lund University, SE-223 62 Lund, Sweden
[f] Faculty of Environment and Natural Resources, AlbertLudwigs University, Freiburg, Germany
[g] Institut Européen de la Forêt Cultivée, Evariste Galois, 63170 Aubière, France

2.1 Abstract

Windstorms are considered the main disturbing abiotic agent in European forests. They affect the provisioning of Ecosystem Services crucially important at environmental and social levels, and strongly alter forests contribution to climate change mitigation. Due to the multiplicity of forest- related dimensions (e.g. ecology, forest operations, geomorphology, economy, socio-cultural) affected and the complex dynamics set off by windstorms, the design of post-windstorm forest management should be characterized by an interdisciplinary approach able to address multiple environmental and social needs. However, the implementation of such approach is often inhibited by a partial and limited comprehension of windstorm impacts. Despite the existence of a vast literature investigating windstorm consequences on European forests, current research is mainly focused on post-windstorm dynamics affecting environment-related dimensions.

By adopting an interdisciplinary approach, this paper aims at improving and complementing current knowledge on windstorm impacts on European forests. We reviewed current literature on forests-windstorms relationships focusing in particular on the role that interconnections and cascade effects among forest-related dimensions play in post-windstorm dynamics. We performed an in-depth review of 111 articles to detect most recurrent direct and indirect impacts as well as cascade effects among ecological, geomorphological, managerial, economic, socio-cultural, and institutional forest-related dimensions. Our analysis aimed at achieving two main goals: (a) provide a detailed and updated analysis of the most recurrent windstorm impacts on European forests reported in literature ; (b) suggest an innovative approach to analyze windstorm consequences at a systemic level to acquire a comprehensive overview of post-windstorm dynamics.

Our results showed that most of the impacts analyzed in scientific literature belonged to environment-related dimensions (forest ecology, pest outbreaks and geomorphology), while impacts concerning human-related dimensions (i.e., economic, institutional, social and cultural) have seldom been focused on. Furthermore, most of the articles investigated interactions between environmental and ecological components of forests, but failed to consider links between natural processes and societal components of forest-related systems. These knowledge gaps reduce the effective comprehension of windstorm impacts in the short and long terms and overlook the influence of societal-related aspects in post-windstorm forest management. The interdisciplinary approach suggested, besides avoiding dimension-specific forest strategies (i.e. prioritizing silvicultural and ecological aspects), promotes the formulation of a post-windstorm management that act at systemic and comprehensive level supporting forests multifunctionality in a context of natural disturbances intensification.

Keywords: European Forests; Windstorms; Cascade Effects; Interdisciplinary Approach; Forest Multifunctionality; System Thinking

2.2 Introduction

Climate change is greatly influencing forest structure and composition, strongly affecting forest ecosystem functions as well as the provisioning of forest ecosystem services (ES) and ultimately benefits for humans (Forzieri et al., 2021; Hanewinkel et al., 2013; Messier et al., 2019; Stritih et al., 2021). Covering 33% of the European territory, forests provide a large variety of ES fundamental for the fulfilment of environmental and societal needs, as well as for tackling challenges posed by the current climate change crisis (Blanco et al., 2017; FOREST EUROPE, 2020; Härtl et al., 2016; Nordström et al., 2019). Recent studies on accounting for ES at European level estimated that forests are the green infrastructure providing the highest value of ES (Nordström et al., 2019; Winkel et al., 2022). Though just partly reflected on explicit market value, forests account for 47.5% of the total supply of ES estimated at European level, especially for what concerns water purification, timber provisioning, flood control and carbon sequestration (Vallecillo et al., 2019; Vysna et al., 2021).

Climate change is also increasing the frequency and severity of natural disturbances that represent one of the greatest threats to forest ecosystems, and pose important questions about the adaptability of current forest management approaches to future challenges (Lundholm et al., 2020; Messier et al., 2019).

Wind has been identified as the main abiotic disturbance agent in Europe (Forzieri et al., 2020; Roberts et al., 2014; Spinoni et al., 2020). Between 1950 and 2000, windstorms accounted for 53% of the total damage caused by abiotic agents to European forests, totaling more than 900 million m^3

of windthrown timber with an average yearly damage of 18.7 million m^3 (Gardiner et al., 2013; Schelhaas et al., 2003). Though often unevaluated and poorly studied, wind damage also affects many other relevant forest-related ES, such as water purification and nature-based recreation (EEA, 2017; Romagnoli et al., 2022). Under conditions of increasing vulnerability and exposure of both forests and forest-related systems, and considering the forecasted increase in windstorms frequency and severity (Forzieri et al., 2021), acquiring a broader vision of windstorm impacts that encompasses both environmental and human forest-related dimensions is necessary.

However, the most common approaches related to post-disturbance forest management mainly adopt a unidimensional and discipline-specific approach (Messier and Puettmann, 2011; Nikinmaa et al., 2020; Rist and Moen, 2013) with in-depth analyses of disturbance consequences in single forest-related dimensions (e.g. silviculture, forest operations, forest value chain, etc.) or in one specific component/aspect of the forest system (e.g. forest regeneration, species composition, timber prices fluctuations, etc.). The tendency of investigating disturbance consequences only considering a small subset of targeted aspects (e.g. physical, biological, or social), has been observed in relation to several forest damaging agents (e.g. forest fires, droughts and bark beetles outbreaks) (Filotas et al., 2014; Härtl et al., 2016; Huber et al., 2013; Messier et al., 2019) . In line with these trends, most of the scientific literature investigates windstorm impacts on forests adopting a discipline-specific approach, with a predominant focus on environment-related dimensions and forest management aspects (Härtl et al., 2016; Leverkus et al., 2018a; Müller et al., 2019). In particular, most studies focus on changes in ecological and silvicultural terms, and on tailored salvage logging techniques to be implemented after damaging wind events (Senf et al., 2019).

Due to this lack of transdisciplinary and systemic analysis, current research on forest-windstorms relations runs the risk of getting only a partial view and understanding of the broader picture of windstorm consequences (Filotas et al., 2014; Wunder et al., 2021). Post-windstorm response dynamics driven by cascade effects, causal relations among forest-related dimensions, and spillover impacts that occur within and between environmental and human components of the forest system remain often unexplored (Aquilué et al., 2020; Heinimann, 2010).

This paper is a first attempt to overcome knowledge fragmentation and sectorization of the analysis concerning windstorm consequences and post-windstorm management in European forests. To this aim, inspired by the system thinking approach, we performed a transdisciplinary analysis of the scientific literature to gain a better understanding of direct and indirect windstorm impacts on European forests and forest-related systems.

The methodology adopted aims to go beyond the siloed and discipline-specific approach adopted in the existing literature, and to provide a systemic analysis of causal relationships and cascade effects among environmental, managerial, economic and institutional forest-related domains affected by windstorms.

The final goal of the paper is to complement current scientific research on windstorms-forest relationship, providing an improved understanding of windstorm impacts on European forests and stressing interconnections and cause-effects relationships among forest-related domains. To achieve this, we reviewed the existing scientific literature to identify: i) the forest-related dimensions that are most frequently analyzed in research, ii) the direct and indirect windstorm effects investigated in the scientific literature, iii) whether and to what extent current research addresses the role of causal relationships in post-windstorm recovery. This analysis aims at highlighting the role played by cause-effects linkages in post-windstorm recovery, detecting the drivers that might reduce vulnerability and boost adaptability both at ecological and social level (Filotas et al., 2014; Klein et al., 2019; Messier et al., 2016).

We believe that this study can be useful to inform both practitioners and policy makers in developing and implementing multi-purpose management strategies that simultaneously ensure resilience and resistance of forest ecosystems to windstorms (and to future extreme events in general) and the fulfillment of multiple stakeholders' needs through the provisioning of multiple forest ES (Fischer, 2018; Nordström et al., 2019; Wunder et al., 2021).

2.3 Materials and methods

A systematic mapping approach (Grant and Booth, 2009; James et al., 2016) was adopted to identify and chart the variety of direct and indirect windstorm impacts detected in the literature. Considering the variety of disciplines and dimensions involved in the analysis, this approach has been preferred to a systematic review (Grant and Booth, 2009). In fact, a systematic mapping approach is as rigorous and objective as a systematic review, but rather than aiming at answering specific and single questions it aims at fully analyzing existing literature related to multi-faceted questions (James et al., 2016). This approach aims at giving a wide representation of the scientific knowledge produced in relation to a certain topic, allowing to identify information clusters, i.e. issues that have been studied in depth, and connections among the different disciplines/subtopics included in the analysis (Wohlin et al., 2013) or, conversely, potential knowledge gaps (Peters et al., 2015). The clear and strong visual outputs of this approach are accessible and understandable also for non-experts and policy makers. Moreover, outcomes of systematic mapping can trigger more comprehensive and detailed analysis (Grant and Booth, 2009; Wohlin et al., 2013) or underpin policy formulation (James et al., 2016). Causal mapping has been already applied in several studies of complex environmental related issues affecting multiple system dimensions (Bi et al., 2021; Özesmi and Özesmi, 2004; Powell et al., 2018), such as: wildfires (Wunder et al., 2021), flood risk management (Rehman et al., 2019), and landscape management (Gretter et al., 2018), and it has proved to be particularly effective in representing the functioning of the system under analysis (Fairweather, 2010).

In this study, our causal map provides a systemic overview of post-windstorm dynamics in forest systems, identifying cause-effect linkages triggered by windstorm impacts, feedback loops and interconnections among multiple forest-related components, and interactions between societal and environment-related drivers. The graphical representation of the interactions proved to be an effective tool to improve the comprehension of the multiple dynamics arising in forest-related systems in response to windstorms.

To ensure reliability and transparency of our study, the whole literature review process and causal representation of the results took inspiration from the framework for systematic mapping in environmental science proposed by James et al. (2016). Our review followed four main steps, each of them composed by several sub-actions: i) Design of the review approach; ii) Papers searching and screening; iii) Data collection and categorization iv) Results discussion and graphical visualization. Each step and the associated sub-actions are presented in the next sections.

2.3.1 Design of the review approach

To ensure the coverage of all fields relevant in the analysis of forests-windstorms relations, an interdisciplinary team composed by researchers from five different forest-related fields was established, including: forest ecology and silviculture, forest mechanization, forest entomology and pathology, forest policy and economics, and geomorphology.

As a first step, to clearly frame the scope and the "setting" of our review, we identified via existing scientific literature the forest-related domains mostly affected by windstorms in Europe (Fleischer et al., 2017; Forzieri et al., 2021; Gardiner et al., 2013; Härtl et al., 2016; Hlásny et al., 2021; Leverkus et al., 2018b; Wunder et al., 2021). These include (i) forest ecology and silviculture; (ii) forest operations and logistics; (iii) forest policy and socioeconomics; (iv) ES provisioning; (v) geomorphology and (vi) forest entomology. These six forest-related domains have underpinned the identification of further dimensions and variables to be included in the analysis.

After having identified the forest-related domains, we proceeded to keywords identification for papers selection. Keywords identification has been a crucial step to ensure consistency within the review and across the domains identified. Formulation of searching strings followed a two-step procedure: i) firstly, we identified a base query including relevant keywords for all of the six domains, i.e., "forest* OR woodland AND wind* AND disturb* OR damage"; ii) secondly, for each domain we added a few specific keywords in order to better tailor the analysis to each forest-related domain. Ultimately, eight queries were defined (Table1). Literature search was performed between September and December 2020 in the Scopus® database, copyright Elsevier, using title, abstract and keywords search. To guarantee consistency and reliability in articles selection and screening stages, the main features of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach have been adapted to the scope of the review and combined with the methodology adopted (Figure 2.2) (Page et al. 2021).

Table 2.1 - List of strings used for literature search. Note that the base query is the same across all six forest-related domains ("forest* OR woodland AND wind* AND disturb* OR damage"). Domains-specific keywords were then added to perform a literature search

Forest-related domains	Strings of keywords used for literature search
Forest ecology and silviculture	forest* OR woodland AND wind* AND disturb* OR damage* AND ecolog* or management* OR "climat* chang*"
Forest operations and logistics	forest* OR woodland AND wind* AND disturb* OR damage* AND harvest* OR "salvage logging"
Forest policy and socioeconomics	forest* OR woodland AND wind* AND disturb* OR damage* AND institution* AND govern*
	forest* OR woodland AND wind* AND disturb* OR damage* AND soc* AND economic* OR financial*
Ecosystem services provisioning	forest* OR woodland AND wind* AND disturb* OR damage* AND ecosystem* AND service*
Geomorphology	forest* OR woodland AND wind* AND disturb* OR damage* AND sediment* or largewood
	forest* OR woodland AND wind* AND disturb* OR damage* AND flood
Forest entomology	(forest* OR woodland) AND wind* AND (disturb* OR damag*) AND (beetle* OR pest* OR "bark beetles" OR "wood boring insects" OR "wood-boring insects" OR pathogen* OR outbreak*)

2.3.2 Paper searching and screening

While queries and inclusion/exclusion criteria were defined by the research team as a whole, each reviewer was responsible for articles searching and screening pertaining to his/her specific field of expertise and the corresponding forest-related domain.

The screening procedures was identical for all the reviewer and followed the steps described below:

i) A search of title, abstract and keywords was performed for the searching strings defined.

ii) Databases merge: articles retrieved from different searching strings belonging to the same forest-related domain were merged into a single database. Secondly, a duplicate cleaning to avoid double records was performed. This step leaded to the creation of six databases, one for each forest-related domain.

iii) Preliminary screening of title and abstract to ensure consistency with the review's purpose and inclusion/exclusion criteria.

iv) Articles with title and abstract matching with review criteria were full analyzed via full-text reading to assess pertinence and full compliance with the aim of the study.

Once the screening procedure was finalized a common database was created by merging the databases from the different forest-related domains. Subsequently, a second duplicate cleaning procedure was carried out. This merged database included all the articles assessed as relevant and pertinent to the review's scope in the six forest-related domains investigated.

At the end of this process and consistently with PRISMA approach guidelines, 13 papers identified via citation searching and scholars' consultation were added to the articles found via searching strings because of their particular relevance to the study of the issues investigated.

This final pool of papers was scrutinized, and data were extracted, following detail coding and categorization procedures, as described in the following section.

2.3.3 Analysis and categorization of the results

The pool of papers selected with the review process was analyzed in depth implementing narrative and content analysis approaches (Pawson, 2002; Snyder, 2019). The information extracted was categorized based on a combination of generic and topic-specific fields (James et al., 2016) in three different databases:

1) Generic information, including:

Bibliographic information; storm(s) analyzed; location of the study; data collection methodology (e.g. qualitative inquiries with direct stakeholders involvement; comparative analysis; quantitative data collection; etc.);

2) Data specifically related to the storm studied:

Year; countries and/or European geographical areas interested; maximum wind speed recorded; reported damage related to (i) study area of the article and (ii) overall areas hit by the storm in terms of aggregated of forest cover loss (both in ha and m^3), insured losses and estimated economic damage;

3) Data related to windstorm impacts:

- Direct and indirect windstorm impacts were analyzed in each article.

  Direct windstorm impacts are those impacts that directly affect a variable/component of the forest-related domains identified for the analysis. Indirect impacts are spillover or cascade effects that may follow from direct windstorm impacts. It is worth mentioning that indirect effects can be recorded in the same forest-related domain of the direct impact or in a different one.

  Indirect impacts were recorded only when specifically mentioned in the article. It is worthy highlighting that not all direct impacts retrieved had cascade effects.

Time span and legacy of impact (i.e., whether the impact is expected to have consequences in a time range of 5-10-15-50 years after the event).

"Nature of the impact" (*sensu* Thom and Seidl, 2016), to indicate whether a specific windstorm impact might eventually lead to (i) an improvement (e.g. increase in biodiversity) or (ii) a decrease (e.g. in regulating services) in the variables considered. If an article mentioned a cascade effect but did not specify whether it had brought positive or negative consequences, neutrality was assigned to this aspect.

The data collection of direct and indirect windstorm impacts was based on a specific hierarchical coding (Figure 2.1). The core idea of the coding system was to grasp the cascading effect of windstorms along and among multiple components of forest-related system domains. Thus, windstorm impacts on forest-related components belonging to the same domain were grouped into hierarchical categories (Filotas et al., 2014; Powell et al., 2016; Sterman, 2001). The forest-related system taken as a whole was broken down into forest- related dimensions, forest- related macrocategories and forest-related components (Figure 2.1).

Dimensions refer to forest sub-systems affected by windstorms and largely overlap with the forest-related domains underpinning our literature analysis. The only forest-related domain that has been broken into multiple dimensions is that of forest policy and socio-economics, that has been divided into institutional, economic, cultural and social dimensions. The final forest-related dimensions considered for the analysis are: forest ecology, forest operations, geomorphology, risk of pest outbreaks, ES provisioning, economy, institutional, cultural and social.

To increase the degree of accuracy in identifying windstorm impacts, the dimensions were further distinguished in macro-categories. Macro-categories can be viewed as conceptual subsets within forest-related dimensions (i.e., forest ecosystem dynamics, stakeholders' relations, pest outbreak risks, etc.). Macro-categories are in turn comprised of specific forest-related components that have been affected by windstorms. Forest-related components are specific forest-related variables or stakeholders that have been directly or indirectly affected by windstorms. Figure 2.1 provides a visual representation of the coding system used for data categorization, while figures 2.2 presents a practical example of forest-related dimension breakdown in macrocategories and forest-related components. The complete lists of variables composing macro-categories and specific forest-related components is available in Appendix 2.

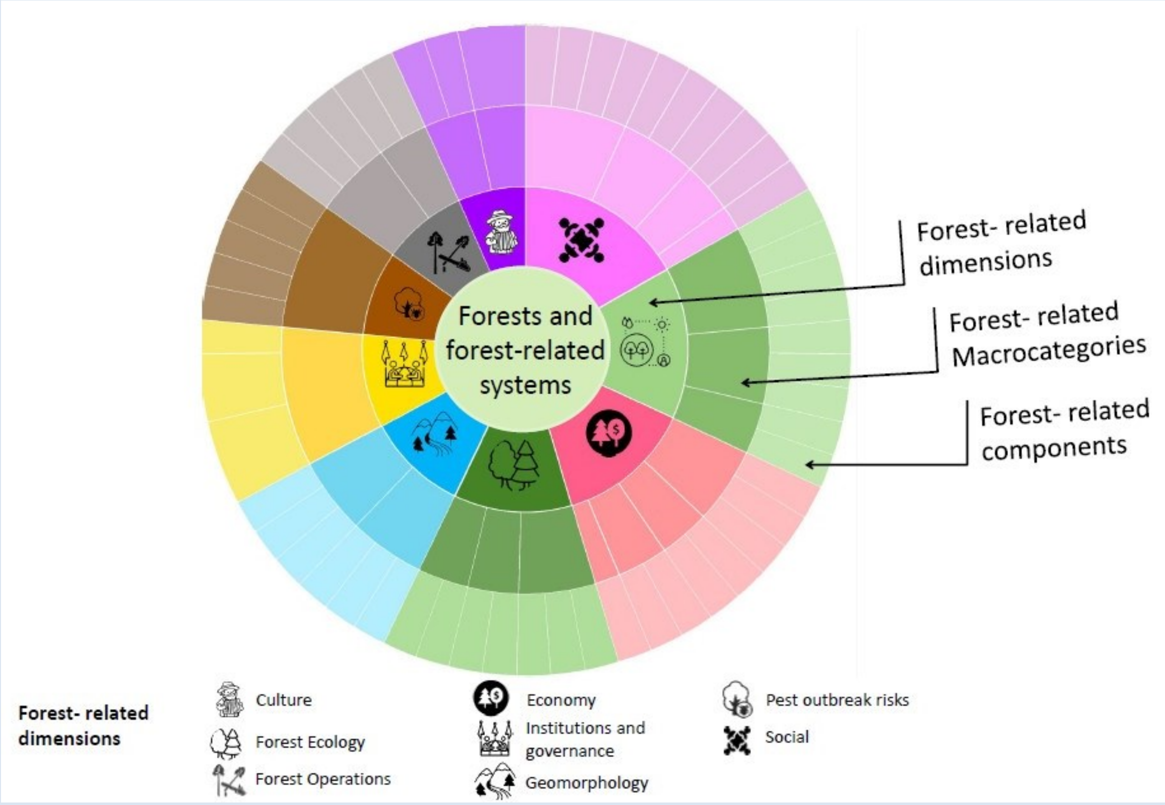

Figure 2.1 *- Visual representation of the coding system used to categorize direct and indirect windstorm impacts*

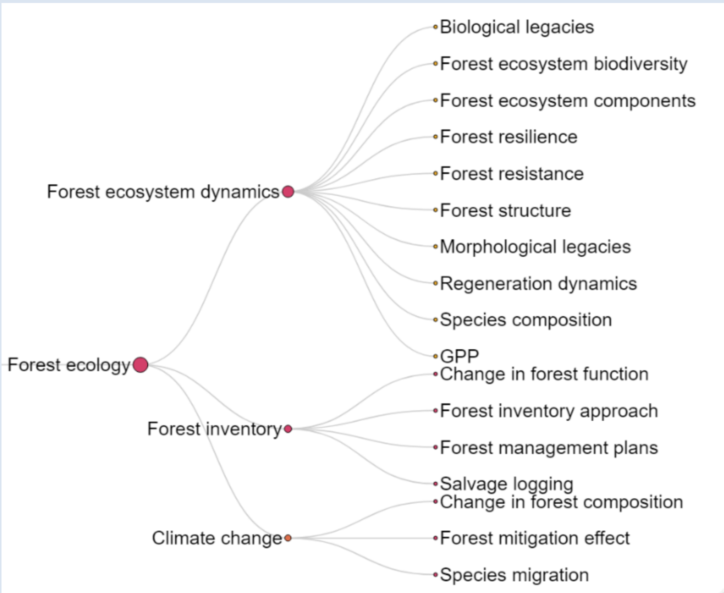

Figure 2.2 - *Example of coding system application. The Forest Ecology dimension is decomposed in macrocategories (first three branches) and several forest-related components*

Following this coding structure, direct and indirect windstorm effects were detected in the selected literature, paying particular attention to cascade effects and cause-effect linkages within and among forest-related dimensions. Appendix 2 provides an example of the process followed to categorize impacts.

2.3.4 Discussion and graphical visualization of the data collected

Once windstorm impacts were categorized, they have been graphically represented in a causal map (Kim, 1999; Scavarda et al., 2006; Sterman, 2001). Causal relations among windstorm impacts and forest-related components have been visualized using arrows (Figure 2.7), where the direction of arrows defines the influencing and the influenced variables. The color of the rectangle identifies the corresponding forest-related dimension. Bearing in mind the nature of the relations and that windstorm impacts simultaneously affect several forest-related dimensions, we allowed multiple interconnections between causal map elements and that, depending on the number of windstorm impacts, several chains of causality can start from a single element.

2.4 Results

This section presents the most relevant descriptive features of the collected literature, namely: (i) summary results of the searching and screening process, (ii) descriptive features of the publications retrieved (year of publication, geographical area and windstorms investigated), (iii) frequent forest-related dimensions investigated in relation to windstorm impacts (iv) relevant primary and secondary windstorms impacts assessed in the literature.

2.4.1 Results of articles searching and screening process

The keyword searching process led to the identification of 2979 articles in the Scopus database (Figure 2.2). As outlined in the "Material and Method" section, a paper screening procedure was undertaken to discard the articles incompatible with or irrelevant for the review scope. A first screening of title and abstracts reduced the number of eligible articles from 2979 to 505. Furthermore, this pool of papers underwent an in-depth reading procedure to assess compliance with inclusion and exclusion criteria and ensure full pertinence to the specific goals of the review. The final pool of scientific publications matching the review criteria amounted to 98 articles. To these, 13 articles identified from citation searching were added because considered extremely relevant for the scope of the study, for a total number of 111 papers. Figure 2.3 reports the papers analyzed in each step of the review skimming procedure. The full list of papers retrieved for each forest-related domain in each step of the procedure are in Appendix 3.

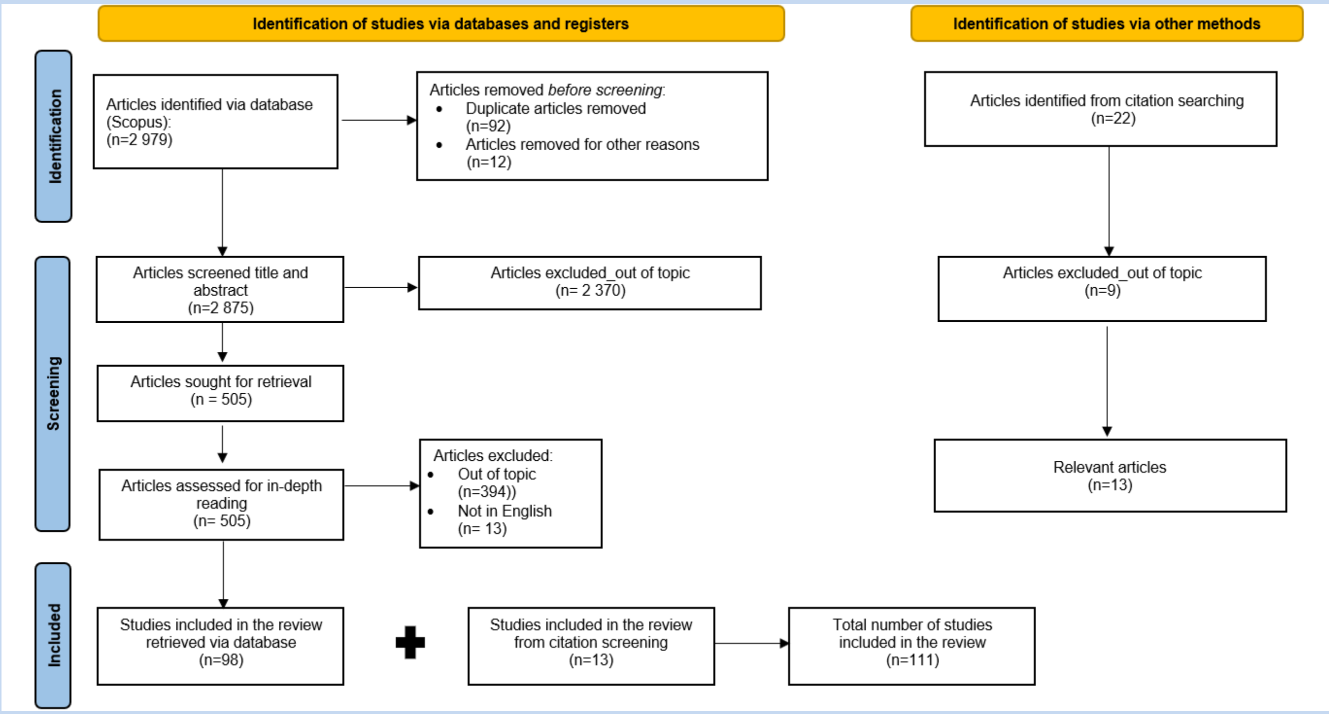

Figure 2.3 - Flow diagram of searching and screening procedures implemented in the literature review based on PRISMA approach. Diagram adapted from Page (2021)

2.4.2 Publication period and geographical area

The publication period of eligible articles retrieved ranges from 2000 to 2020. As the trend red line shows in Figure 2.4, during this time frame there has been a constant increase in publications related to forest- windstorms relationships, with a spike between 2010 and 2020 (Figure 2.4).

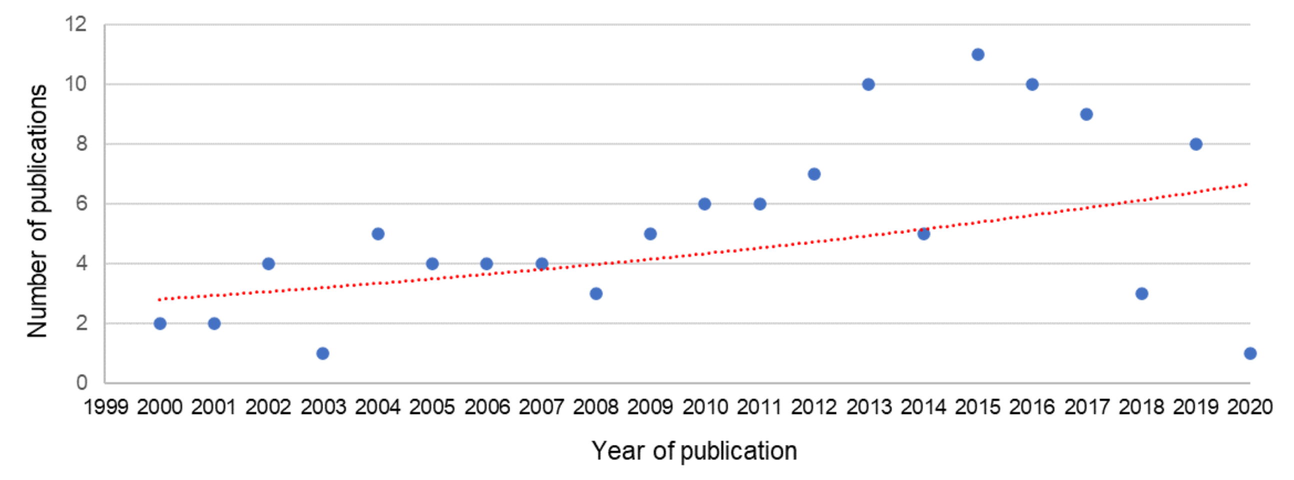

Figure 2.4 - *Numbers of articles published per year. The red dotted line indicates the trend during the time frame considered in the review*

Identifying the specific storm studied in the articles was not always straightforward. Over half of the scientific articles (n=60 publications) either did not name the specific windstorm analyzed or focused on local windstorms with a low wind severity, making it difficult to identify a specific storm. A smaller share of studies focused on the main large-scale windstorms that affected Europe in the last two decades, namely Lothar (n=7 publications) hitting France, Switzerland and Germany in 1999; Elizabeth (n=8 publications) hitting Slovakia in 2004, Gudrun (n=9 publications) hitting mainly Sweden, Norway and the United Kingdom in 2005 and Kyrill (n=5 publications) hitting mainly France, Germany and Austria in 2007.

Regarding the locations of the affected areas, most studies were performed in Centre/North-European countries (83.7%). A much lower proportion of studies reported data on windstorms affecting East European Countries (7.3%) and only a limited amount analyzed windstorm consequences on South European countries (3.6%), Italy being the only country investigated. The remaining articles did not specify the geographical scope (3.6%) or targeted the whole of Europe (1.8%). The geographical distribution of the retrieved studies is represented in Figure 2.5.

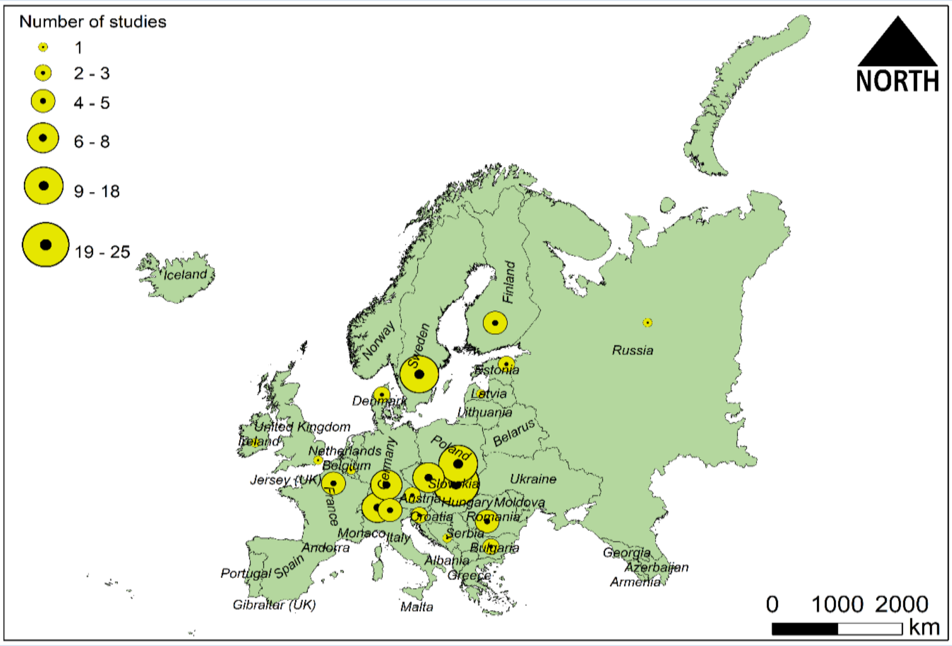

__Figure 2.5__ - Distribution of reviewed studies across European countries. The size of the circles indicates the numbers of studies found for each country

2.4.3 Characterization of primary and secondary windstorm impacts

The final database consists of a total of 476 windstorm impacts, 272 related to direct impacts and 204 to indirect/spillover effects. The lower number of indirect impacts is explained by the fact that 25% of the articles analyzed did not outline spillovers connected to windstorm primary impacts.

Figure 2.6 reports the share of direct and indirect windstorm impacts for all the forest-related dimensions considered.

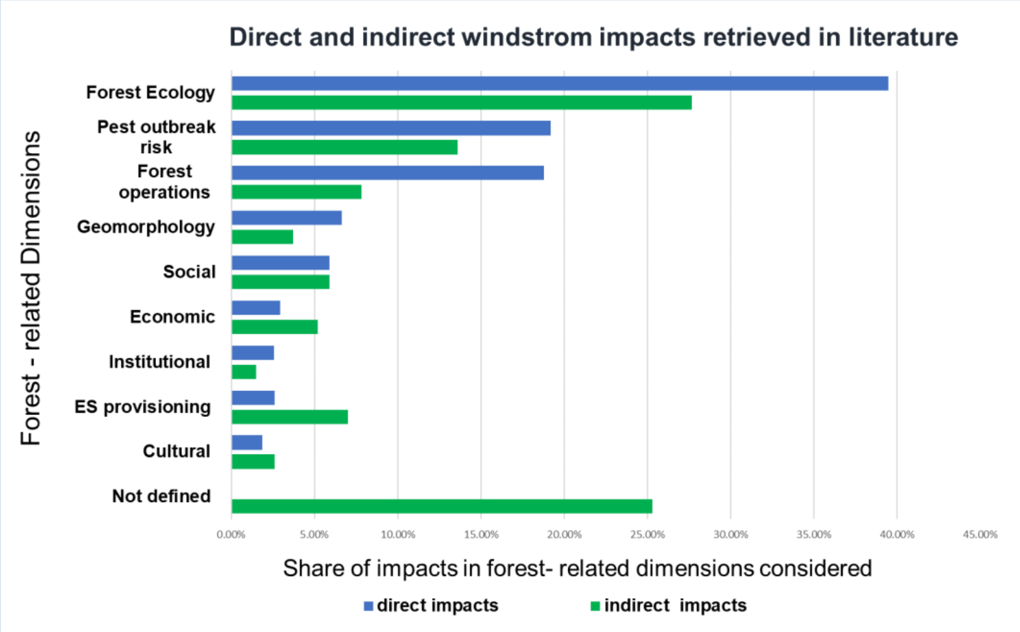

Figure 2.6 *- Share of direct and indirect windstorm impacts detected in the forest-related dimensions analyzed*

Most of the impacts categorized, for both direct and indirect impacts, belonged to environment-related dimensions (forest ecology, pest outbreaks and geomorphology) that together accounted for 63% of the total impacts retrieved. Impacts of windstorms on ES provisioning accounted for only 2.6% of total direct impacts, while they represent 8.5% of total indirect impacts. Considered together, impacts on human-related dimensions (i.e., economic, institutional, social and cultural) accounted for about a quarter of direct (13.3%) and indirect (14.7%) impacts.

Windstorm impacts largely tend to be transboundary, as spillover effects of direct windstorm impacts spread through multiple forest-related dimensions. Figure 2.7 shows the distribution of direct windstorm impacts across forest-related dimensions, identifying which dimensions are mainly affected by primary windstorm impacts.

As an example, if we consider windstorm impacts on the forest operations dimension, we can see that, beyond affecting forest operations management, direct impacts have cascade effects on forest ecology (32.7%), ES provisioning (7.8%) and economics (7.8%) dimensions. Similarly, spillover effects derived from windstorm impacts on the geomorphology dimension have indirect effects on the geomorphological aspects, but also influence ES provision (33%) and cultural dimension (16.7%). The same situation is observed in human-related dimensions. Direct windstorm impacts at economic level generate cascade effects in social (25%), institutional (12.5%) and forest ecology dimensions (12.5%). Likewise direct impacts at institutional level have cascade-effects distributed across social (42.8%), economic (28.5%) and cultural (28.5%) dimensions. Over the forest-related dimensions investigated three have a lower degree of cross-dimensionality: forest ecology, pest outbreaks and social dimensions. In these cases, direct impacts have indirect effects mainly distributed within the same dimensions (Figure 2.7).

2.4.4 *Transdisciplinary analysis of direct and indirect impacts*

Inspecting topics and issues analyzed within each forest-related dimensions, some general patterns can be drawn of the most common direct and indirect windstorm impacts analyzed in the literature.

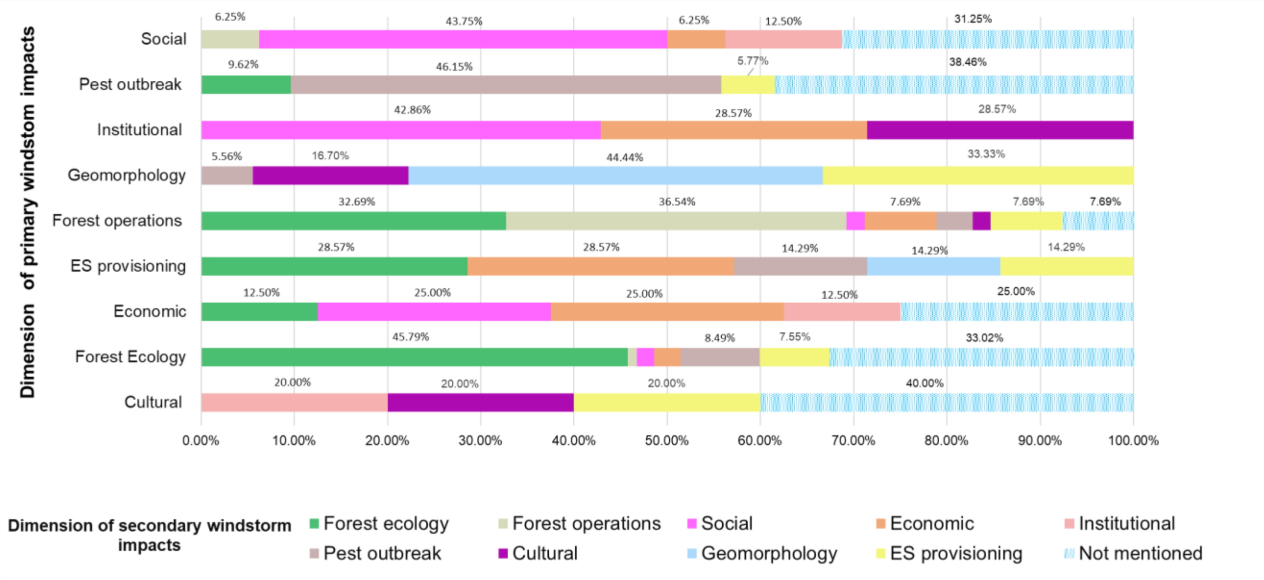

Figure 2.7 *- Breakdown of, and relationship between, different direct windstorm impacts across all forest-related dimensions*

The forest ecology dimension recorded the highest number of both direct (39%) and indirect (27.8%) impacts. Half of the direct windstorm impacts on forest ecology refer to consequences on forest ecosystem dynamics (51.9%), primarily on forest structure, forest species composition, and regeneration dynamics. As shown in Figure 2.7, direct windstorm impacts at ecologic level mainly have consequences in the same dimension (45.8%), affecting forest ecosystems dynamics and functions such as forest ecosystem biodiversity, forest resistance and mitigation effect for pest outbreaks.

Articles investigating windstorm impacts at ecological/silvicultural level mainly focused on direct and indirect windstorm consequences on forest ecology and pest outbreaks risk and, to a lesser extent, on changes in regulating and provisioning ES. Cascade effects on societal-related dimensions (i.e. economic, institutional, social and cultural) have been addressed only in five articles, that pointed out how changes in forest structure and composition could influence the recreational value of forest or wood markets dynamics.

Windstorm consequences on pest outbreaks constitute the second most studied topic among the reviewed literature, accounting for 19.2% of the total direct impacts and 13.6% of the indirect ones. All articles investigating windstorm-bark beetles relationship stressed how windstorms play a direct role in increasing risks in pest outbreaks. Damages caused by bark beetle infestations after windstorms are likely to strongly affect forest ecosystem dynamics (Mezei et al., 2014). This is also reflected in our analysis which indicates that forest ecology is the forest-related dimension mostly impacted by pest outbreaks (9.6%) aside from changes in bark beetles population dynamics and pest outbreaks (Figure 2.6). In the view of the devasting effects that bark beetle outbreak cause at the ecological level, a large share of articles (40%) investigated prevention practices to manage windthrown and damaged logs.

While cascade effects among windstorms – pest outbreaks – forest ecology dimensions are largely studied, spillover effects of wind disturbance and pest outbreaks interaction on socio-economic dimensions have not been addressed extensively. Only one article on post-windstorm pest outbreaks mentioned any consequences on cultural or economic aspects (Fleischer et al., 2017).

Forest operations was identified as one of the forest-related dimensions mostly affected by windstorms, representing 19.2% of total direct impacts. Windstorms cause important changes in the business-as-usual of forests and logging operations. As such, most of the direct windstorm impacts on this dimension (86.6%) are related to changes in management of forest operations and logistics. Such changes have, in turn, direct and indirect cascade effects on several forest-related dimensions. Regarding the environment-related dimensions, forest ecology is the one most affected by spillover consequences (32.7%). Cascade effects affecting societal-related aspects are observed at economic level (7.7%), mainly in timber-related sectors and on the income of large-scale and non-industrial private (NIP from hereafter) forest owners. Post-windstorm forest operations are also likely to have impacts on the labor market linked with the logging sector. These operations are generally riskier than business-as-usual logging and harvesting operations and because of that they generally require the employment of high-specialized and skilled workforce. This adaptation in workforce expertise could affect labor market dynamics, potentially leading to operators replacement, especially if local forest operators' skills are not adequate to work in difficult terrain (Kärhä et al., 2018b; Lidskog and Sjödin, 2015). However, only two among the articles analyzed addressed the issue of workforce skills adaptation. Likewise, how salvage logging affects the provision of cultural services as well as landscape value and perception was not addressed in the analyzed literature.

Among the environment-related dimensions analyzed, the geomorphology dimension accounted for the lowest percentage of direct (6.6%) and indirect (3.3%) impacts. Only 7 articles reported consequences at the geomorphological level, with the case study areas being located solely in the mountainous environment. In terms of direct impacts, all the 7 articles investigated negative windstorms effects on mountain slope dynamics, in particular on slope instability and sediment production. While, for what concerns spillover effects, our results stressed important cascade effects of post-windstorm slope dynamics on the provision of ES (33.3%).Regulating ES was identified as the ecosystem service mostly affected by changes at geomorphological level (Haliuc et al., 2019; Scheidl et al., 2020).

Windstorm impacts on human-related (socio-cultural, economic and institutional) dimensions remain overlooked in the literature. Among these dimensions, the focus in the literature has been placed mainly on consequences on economic and social levels, leaving aside impacts on institutional and cultural aspects. The latter two represent 3% of both direct and indirect impacts. As far as the economic dimension is concerned, our results show that this dimension is mainly affected at indirect level (indirect impacts: 5.2%; direct impacts: 3%). Economic consequences of windstorms mainly examined in the literature concern negative impacts on the economy of different timber-related sectors with relevant spillovers not only at financial level but also on social and ecological aspects. At the social level, the focus revolves around direct (5.9%) and indirect (5.5%) windstorm consequences on NIP forest owners' livelihood and well-being.

The analysis on ES provisioning revealed that this dimension, like the economic one, seems to be more affected at indirect level by spillover and cascade effects triggered by windstorm impacts in other forest-related dimensions. All direct impacts reported a decrease in stand wood biomass, while cascade effects from other dimensions mostly lead to a reduction in several regulating services (i.e. carbon sink capacity, climate change mitigation, soil erosion etc.) , and at minor extent, in forest recreational functions. Changes in ES have, in turn, several spillover consequences on various forest-related dimensions, in particular on ecological and economic aspects.

2.5 Discussion

Before discussing specific patterns and interconnections between windstorm direct and indirect impacts, it is worth focusing the attention on some general patterns related to the distribution of scientific articles. The review showed a strong clustering of scientific research on North and Central European countries. Due to the higher frequency of high intensity windstorms, the large extent of forested land at these latitudes, and the large proportion of wind damage-prone conifer plantation forestry in these countries, this finding was not surprising (Copernicus, 2022; Forzieri et al., 2020; Roberts et al., 2014). However, the almost total absence of analysis regarding windstorm impacts on South European forests shows an important knowledge gap, especially when considering that future wind hazards are forecasted to change their spatial patterns (Spinoni et al., 2020).

Nonetheless, some new research threads to filling this gap are rising. Starting from 2021 several scientific articles analyzing the impact of the Vaia windstorm in the Italian alpine forests were published (Costa et al., 2021; Marangon et al., 2022; Negro et al., 2021; Pellegrini et al., 2021; Pilli et al., 2021; Vaglio Laurin et al., 2021). Although these works were not included in the analysis due to the review time boundaries (December 2020), these articles deserve to be mentioned here because of their novelty in investigating windstorms impacts on South European and mountain forests. Given the diversity of south-European forests from North/Centre-European ones, these studies can bring in relevant contributions and enrich the discussion about post-windstorm management strategies at European level.

2.5.1 Visualization of impacts: cause effects linkages and cascade effects

Our results revealed that the current scientific knowledge is characterized by a strong focus on environmental and natural processes that follow or/and are triggered by windstorms. Impacts and cause-effect linkages affecting socio-economic and institutional dimensions have received much lower attention. Furthermore, for what concerns consequences on socio-economic aspects, stronger emphasis is placed on tangible aspects directly connected to forest-related sectors, such as financial trends in wood-forest supply chain, financial subsidies allocated to forest owners and post-windstorm management strategies implemented. In contrast, non-tangible aspects such as changes in cultural services or societal wellbeing were very rarely mentioned.

Although the articles in our review pointed out how windstorms impact differently and with various intensity a multiplicity of forest-related dimensions, this was not sufficient to state that the literature analyzing forest-windstorm relationships is truly transdisciplinary. Post-windstorms interactions between natural and societal components of forest-related systems have been poorly investigated (Bi et al., 2021; Messier et al., 2019).

To gain a systemic understanding of windstorm impacts on forests and forest-related systems we represented graphically post-windstorm dynamics as well as direct and indirect impacts reported in the literature (Figure 2.8). The process of mapping allowed us to gain a transdisciplinary understanding of windstorm impacts, also stressing causality and interconnections between human agency and environment related drivers.

Figure 2.8 displays the most relevant windstorm impacts analyzed in the articles considered. Interactions among dimensions and forest-related components have been represented drawing inspiration from Causal Loop diagram (Fairweather, 2010; Sterman, 2001), identifying factors that escalate or mitigate windstorm impacts at environmental and/or social level and boost/ reduce forest-system ability to recover from wind hazards. Because of the complexity of these relationships, not all the impacts and consequences retrieved are reported in Figure 2.7 – rather we have decided to represent the most recurrent and relevant ones.

The most relevant direct windstorm impacts reported in the literature concern the ecological dimension. As expected, impacts at ecological level are widespread within the map reporting both detailed consequences on forest ecology and cascade effects on other forest-related dimensions. In particular the causal loop composed by (i) forest ecosystem dynamics, (ii) forest structure and composition, and (iii) regeneration dynamics plays a central role in forest-system post-windstorm dynamics and gives rise to several direct and indirect impacts (Fischer et al., 2002; Fischer and Fischer, 2012; Simon et al., 2011; Vodde et al., 2015). These three aspects mutually influence each other but also are determinant in shaping the composition of future forests, as well as forest recovery policies to be implemented after windstorm (Vodde et al., 2009). Changes in forest structure and composition and in forest ecosystem dynamics have implications in several forest-related dimensions such as forest operations, pest outbreak mitigation strategies and ES provisioning(Havašová et al., 2017; Kobler et al., 2015; Schütz et al., 2006; Szwagrzyk et al., 2018) . For what concerns ES provisioning, the highest number of spillover effects have been reported in forest protection function, gross primary production (GPP) and CO_2 absorption. However, changes in ES are not only directly generated by windstorms impacts. Service provisioning is also strongly sensitive to time variable, namely time since disturbance, that determine how the supply of the service could change after the event.

The management of windthrown trees and other biological legacies (i.e. stumps or snags) left by the storm appears to be a critical aspect in post-windstorm forest management, playing a crucial role in the ecological response of forest ecosystems to wind hazards. If on the one hand biological legacies can benefit forest recovery and regeneration processes (Szwagrzyk et al., 2018; Valinger et al., 2014), on the other hand they can heavily interfere with established management objectives (Fidej et al., 2018) and decrease forest resistance to other natural disturbances such as pest outbreaks or fires (Havašová et al., 2017).

Damaged wood laying on the ground acts as breeding resource for beetle populations, with the potential to promote a large and relatively fast increase in populations size and severity of pest outbreaks (Eriksson et al., 2005; Grodzki and Fronek, 2019; Louis et al., 2014). Pest outbreaks in wind-affected forests are a well-known and well-documented windstorm consequence that might have tremendous impacts on forest ecosystems, increasing forest vulnerability and exacerbating economic damages caused by wind (Mezei et al., 2017). Several European countries have estimated that within a couple of years after a storm, further damage to the forest stock due to bark beetle outbreaks often reached and sometimes exceed the volume of windthrown wood felled by the storm itself (Hlásny et al., 2021; Hroššo et al., 2020; Schroeder and Lindelöw, 2002).

The increase in bark beetles population expected after a storm (Økland et al., 2016) can be mitigated by the implementation of specific forest operations such as salvage logging, deadwood manipulation or decortication (Dobor et al., 2020; Schroeder and Lindelöw, 2002; Taeroe et al., 2019). In particular, salvage logging is one of the most important strategies to mitigate bark beetle outbreaks (Schroeder and Lindelöw, 2002). However, since a large amount of fallen trees need to be removed to make logging an effective prevention strategy (Dobor et al., 2020) this operation might trigger positive or negative cascade effects on forest structure and composition, like increase in species composition (Šustek et al., 2017) or decrease in regeneration dynamics (Fleischer et al., 2017; Leverkus et al., 2015).

Direct and indirect impacts of post-windstorm forest operations are one of the most debated issues because, further than affecting several forest ecosystem dynamics, they also have important effects on various forest-related sectors and stakeholders (Angst and Volz, 2002; Kärhä et al., 2018b). Harvesting plans and log volumes harvested have direct impacts on wood-sector enterprises, not only for what concerns the economy and profitability of these operations, but also in the organization and management of the entire value chain (Björheden, 2007; Broman et al., 2009; Riguelle et al., 2015). The wood harvesting, storage, transportation, and processing sectors have to respond to important changes on (i) the quantity of raw material to be logged and the logging conditions, and (ii) the type of harvesting systems to implement, logistics and storage dynamics, labor competences and forest-related infrastructures (Broman et al., 2006; Caurla et al., 2015; Kärhä et al., 2018b; Magagnotti et al., 2013; Nieuwenhuis and O'Connor, 2001). From the harvesting side, in the case of large number of windthrown and of difficult terrain, mechanized or semi-mechanized harvesting systems are generally used to minimize the hazardousness of logging operations (CTBA, 2004; Kärhä et al., 2018b). These systems, despite improving the safety and stability of the damaged areas and optimizing the productivity of the operations, increase the overall costs and normally require substantial initial investments in equipment and machineries, potentially reducing the profitability of the entire operation (Björheden, 2007; Broman et al., 2006; Nieuwenhuis and O'Connor, 2001).

Windstorms direct impacts and cascade effects on wood sector economy and the revenue of stakeholders could potentially be very large, due to drops in wood prices following e.g., a timber glut in the market, and in the profitability of the entire sector (Brunette and Couture, 2008; Caurla et al., 2015; Fleischer et al., 2017). However, these negative trends can be partly compensated by the introduction of technological advancements, optimization of forest operations, and improvements in forest-related infrastructures. These measures could partially offset the decrease in prices, and increase efficiency of single enterprises as well as of the overall sector (Björheden, 2007; Broman et al., 2009; Hartebrodt, 2004; Kärhä et al., 2018b). All things considered, the severity of windstorm consequences on wood markets and forest related industries is deeply connected with the adaptive and technological ability/possibility of forest stakeholders and wood industry (Riguelle et al., 2015; Sullman and Kirk, 2001b).

Fluctuations in timber market and prices, and changes in forest structure influence private and public forest management and risk mitigation strategies as well as the formulation of policies targeted to large-scale and NIP forest owners. Forest management choices implemented at private level are strongly driven by dynamics and trends predicted in wood and timber markets after the storm, especially for what concerns planting and forest regeneration decisions (Donis et al., 2020; Lidskog and Sjödin, 2014). Forest owners are generally characterized by a strong risk-adverse behavior (Brunette and Couture, 2008; Couture et al., 2016), thus their planting choices are strongly influenced by expected economic risks and profitability of tree species (Brunette and Couture, 2008; Nieuwenhuis and O'Connor, 2001). Projection of timber prices of different species are likely to influence the choice of which species to replant more than their actual vulnerability to future disturbances (Nieuwenhuis and O'Connor, 2001; Nordström et al., 2019; Solár and Solár, 2020). Planting choices in turn have direct influence on future forest composition and consequently in forest vulnerability to future hazards (Blennow, 2010; Sousa-Silva et al., 2018).

Financial subsidies and public compensation policies could be as relevant as future economic projections in shaping private forest owners' management practices (Brunette and Couture, 2008). Besides providing immediate support to mitigate economic losses (Lidskog and Sjödin, 2014) post-windstorm institutional subsidies could guide the choice of which tree species to plant in the recovery phase (Brunette and Couture, 2008).

In relation to the implementation of post-windstorm institutional strategies two important positive spillover effects deserve to be mentioned. Management of wind hazards has been recognized as an opportunity to improve the capacity of forest government agencies to deal with extreme events, and additionally it leads to higher private forest owners' confidence and legitimation of institutions (Lidskog and Sjödin, 2015). Conversely, an unwanted consequence that might follow from government aid is the polarization of power relations among forest stakeholders and in networks and alliances, giving rise to potential conflicts (Caurla et al., 2015). Thus, the acceptance and actual implementation of strategies and programs in response to the risk of wind damage and wind damage events strongly depends on the perceived fairness and equity among different forest stakeholders (Blennow, 2010; Caurla et al., 2015).

A predominant theme in our analysis is the strong and complex relationships existing among forest-related dimensions and their components. For the most part, direct windstorm impacts on one forest-related dimension induced cascade and spillover effects in one or more other dimensions.

Windstorm impacts on the geomorphological dimension are an exception to this pattern, in that they do not spread into other forest-related dimensions, except for the ES provision.

Windstorms have a direct impact on channel and slope dynamics, increasing sediment transportation and in-channel large wood presence (Pilotto et al., 2016). These changes cause important spillover effects on the protective capacity of forests from natural hazards, and on regulating ES and fluvial ecosystem components and biodiversity (Haliuc et al., 2019; Pawlik et al., 2016, 2013). Large-scale disturbances such as windstorm events create and/or reactivate new sediment sources (Pellegrini et al., 2021; Rainato et al., 2021)that, depending on their connection with the channel network, can become an important source of risk for villages located downstream of windstorm affected areas (Mikuś and Wyżga, 2020; Strzyżowski et al., 2018). Furthermore, slope instability caused by large-scale events could lead to sediments displacement also during minor (bankfull-lower than bankfull) flood and rainfall events (Rosgen, 1996).

Tree uprooting caused by wind is the main consequence of damaging windstorms with impacts on water quality and composition. Besides exposing new areas of bare soil, uprooting removes the water absorption capacity of roots. Both these consequences generally promote (i) faster soil saturation, (ii) a subsequent increase in the surficial landslide susceptibility (Gerber et al., 2002) and (iii) different chemical composition of the water solutes (Hellsten et al., 2015).

Large wood recruitment and sediment transport have relevant cascade effects on river and stream biodiversity. If, on the one hand, the extreme floods often associated with windstorms overturn channels morphologies and dynamics, on the other hand they naturally replenish the entire fluvial ecosystem. Therefore, if the primary consequence of windstorms is certainly the disruption of existing ecological niches, subsequently these favor the creation of new habitats for microorganisms and fish fauna thanks to the influx of new material composing the fluvial environment (Coe et al., 2009; Pilotto et al., 2016).

Moving to windstorm impacts on forest cultural values and services, post-windstorm changes in forest landscape are certainly one of the major and most striking windstorm consequence. However, despite it is implicit and expected that extreme windstorms strongly affect landscape composition, in-depth investigations and evaluations of the consequences that loss of forest coverage and other changes in landscape have at economic, cultural, and social levels do not appear in the literature. Few authors reported that bark beetle outbreaks, forest operations and changes in slope and channel dynamics are likely to affect the quality and perceived value of the landscape, affecting its attractiveness and eventually decreasing the provisioning of cultural and recreational activities (Angelstam et al., 2013; Constantine et al., 2012; Leverkus et al., 2021; Mezei et al., 2017). Nevertheless, no consideration have been made on how to integrate visual quality of the landscape with its ecological functions during post-windstorm forest management to fulfill both ecological and societal needs (Angelstam et al., 2013; García-Abril et al., 2019).

Finally, with respect to windstorm impacts on cultural dimension it is worthy to mention a relevant aspect. For the academic community, forest damaging windstorms are seen as an opportunity for knowledge improvements and in-depth exploration of forest ES dynamics after extreme weather events (Brunette and Couture, 2008; Fleischer et al., 2017). Knowledge transfer between academic experts in the fields and local experts (e.g., land and forest managers, forest agencies, etc.) to boost the effectiveness and responsiveness to extreme natural events.

brea

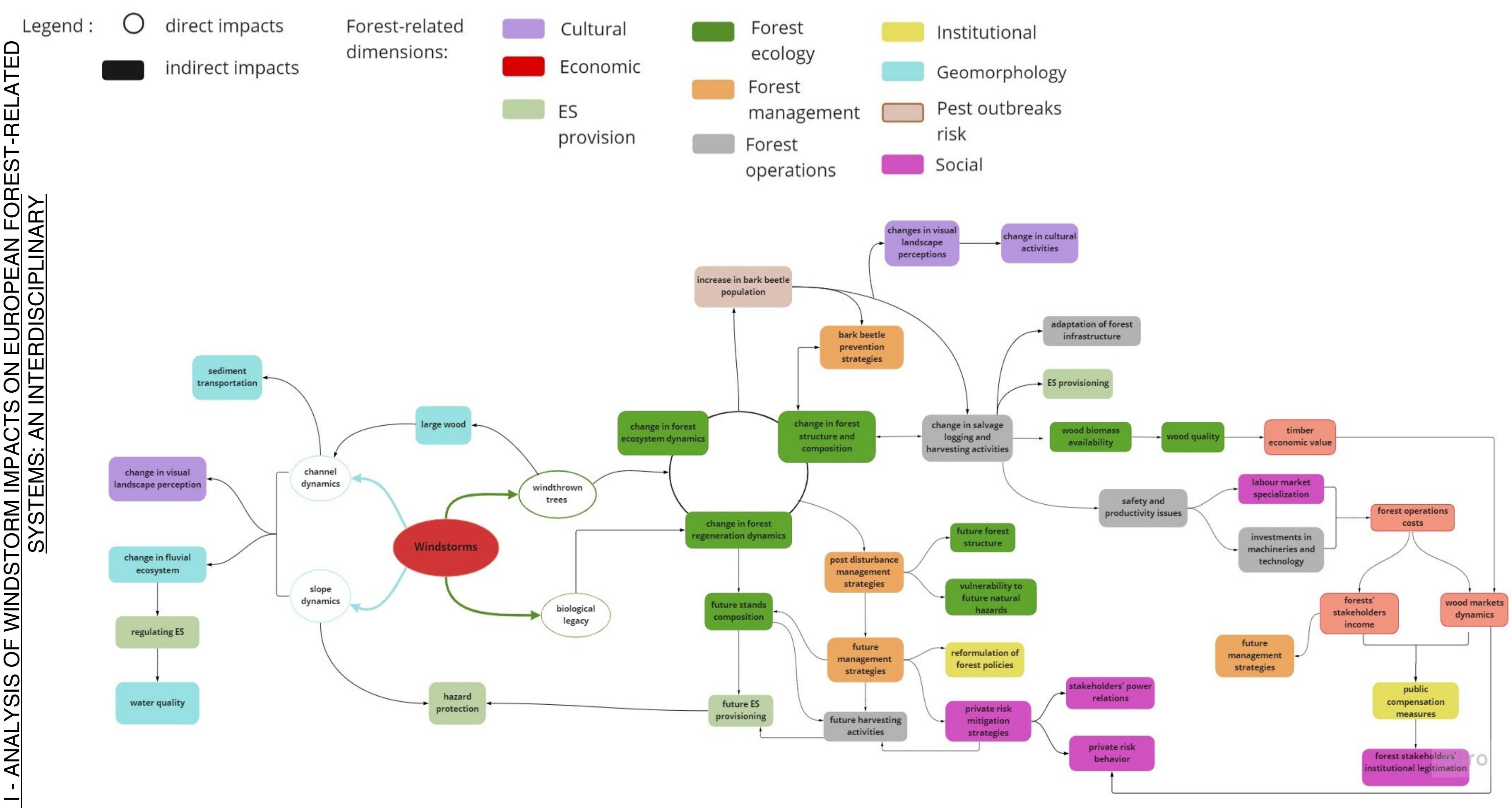

Figure 2.8 *- . Map of the most relevant windstorm cause-effect linkages among forest-related dimensions considered resulted from the literature analyzed. In round shapes are reported direct windstorms impacts, while in rectangle shapes are identified secondary impact*

Role of cascade effects in post-windstorm dynamics and policy formulatio

Examining cascade and spillover effects triggered by post-windstorms dynamics is essential not only for improving the understanding of forest-related systems response to windstorms, but also for reducing the risk of trade-offs and potential conflicts during policy formulation and decision making (Kerner and Thomas, 2014; Rist and Moen, 2013). The complex nature of environmental problems such as extreme events management requires decision-making frameworks able to understand and address a multiplicity of needs and expectations(Arts et al., 2006; Mwangi and Wardell, 2012). However, the variety of stakes and sectors linked with natural resources (i.e. forest resources) management often makes policy formulation and implementation vague and difficult to achieve(Reed, 2008). Nonetheless, several studies pointed out that the achievement of coherent, effective, and robust policies is positively influence by stakeholders' involvement in decision-making process(Acheson, 2006; Patenaude et al., 2019; Scolozzi et al., 2019; Vedeld, 2020).

For what concern the formulation of post-windstorm policies, the limited attention given to the role played by socio-cultural aspects in post-windstorm recovery of forest-related systems as well as the paucity of studies investigating relationships among forest and non-forest sectors' stakeholders are likely to exclude relevant actors from post-windstorm decision-making(Müller et al., 2019; Reed, 2008). This could ultimately overlook potential conflicts arising during policy formulation in relation to forest resource management or even reduce the impact and the efficacy of measures implemented (Kleinschmit et al., 2018; Patenaude et al., 2019).

Adopting a transdisciplinary approach in windstorm impacts analysis would increase awareness and comprehension of the complex forest-related dynamics set off by windstorms, while also acknowledging how social-related aspects influence post-windstorm forest management. This, in turn, would benefit the formulation of post-windstorm forest management strategies that act at systemic and comprehensive level (Blennow et al., 2012; Deuffic and Ní Dhubháin, 2020; Lidskog and Sjödin, 2014; Schou et al., 2015). For example, examining formal or informal post-windstorm practices implemented by affected communities could provide useful insights of which forest functions and services are prioritized by the local community, as well as values and beliefs that guide communitarian action (Halme et al., 2013; Ostrom, 2008). This information could be relevant at decision-making and policy formulation levels to address forest management strategies and eventual trade-offs among, for example, recreation, protection or exploitation functions (Blennow et al., 2021).

Similarly, the influential role that expectations, beliefs and experiences play in large-scale and NIP forest owners' management choices should be taken into consideration by policy makers while designing post-windstorms policy and incentives (Feliciano et al., 2017; Schou et al., 2015; Sousa-Silva et al., 2018).

Cascade effects caused by windstorms on ES without an explicit market value, and on non-forest related sectors should be taken into account in post-windstorm policy design. Windstorms affect a variety of sectors and stakeholders beyond the traditional forest sectors (wood-forest value chains). Considering the needs of these non-forestry stakeholders in the formulation of wind damage-related policies (for the risk management phases of preparedness, intervention, recovery, and prevention) would promote the implementation of different strategies to address expectations of different social groups (Hlásny et al., 2021; Sotirov and Arts, 2018).

These are just some of the knowledge gaps that should be covered for a systemic comprehension of windstorm impacts, and consequently formulate strategies that strengthen forest multifunctionality, reduce vulnerability to extreme events, and support the provision of multiple ecosystem services (Fouqueray and Frascaria-Lacoste, 2020; Sotirov and Arts, 2018).

2.6 Conclusions

Changes in climate and the related increases in intensity and frequency of extreme events are among the greatest challenges that forest-related systems are confronted with nowadays, affecting the provision of ES critically important at ecological and societal level. Windstorms are identified as the most disturbing natural agent for European Forests of the past 50 years. To formulate post-windstorm measures that restore forest ecological functions and simultaneously respond to different socio-economic needs, a complete understanding of windstorm impacts on different components of forest-related systems is needed. Consequently, the formulation of post-windstorm strategies requires a strong awareness of potential cascade or side effects induced by damaging windstorms. A transdisciplinary approach is recommended in the analysis of windstorm consequences and in the design of post-windstorm forest management strategies.

Our review aimed at: (i) reporting on the state of the art of scientific research on windstorm impacts on European forests and forest-related systems; (ii) presenting a new approach for the analysis of forests-windstorms relationships, mapping existing knowledge and exploring connections among environmental, socio-economic, institutional, and managerial forest-related dimensions.

The systemic approach adopted in this review has highlighted the main patterns in the forests-windstorms scientific research, identifying direct and indirect impacts, interconnections and cause-effect linkages most frequently examined.

Our findings indicate that most articles do not consider cascade and spillover effects that windstorm consequences on ecological and environmental aspects have on socio-economic and institutional sectors. This denotes an important knowledge gap and a lack of interdisciplinarity that needs to be addressed in future research.

Due to the variety and diversity of post-windstorms dynamics and forest-related dimensions composing the analysis, we did not examine the role of territorial, environmental and socio-economic features that have a major role in the design of windstorm recovery strategies. Despite this and other limitations derived by the study design (e.g., the exclusion criteria set in our papers selection), our research highlighted the importance and the advantages of adopting a transdisciplinary approach in windstorm impacts assessment, as well as in the formulation of recovery strategies.

The approach adopted could be replicated in other research investigating impacts of climate changes and other natural disturbances (i.e. droughts, fires and pest outbreaks) on forest- related systems, to design effective and long term recovery strategies, able to tackle multiple challenges amplified by the increased occurrence of intense natural hazards.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1– Dimensions and categories used in data collection

Table 2.2 *- Dimensions and categories used in data collection*

Dimensions	Effects		
	Macro-categories	**Micro-Categories**	
Forest Ecology	Forest Ecosystem Dynamics	1) Biological Legacies 2) Forest Ecosystem Biodiversity 3) Forest Ecosystem Components 4) Forest Resilience 5) Forest Resistance	6) Forest Structure 7) Morphological Legacies 8) Regeneration Dynamics 9) Species Composition 10) GPP
	Forest inventory	1) Changes in forest function 2) Forest inventory approach	3) Forest management plans 4) Salvage logging
	Climate change	1) Changes in forest composition 2) Climate mitigation effects of forests 3) Species migration	

Pest outbreaks risk	Pest outbreaks risk	1) Bark beetles 2) Other pathogens 3) Prevention strategies	4) Control Strategies 5) Impacts on society
Forest operations	Forest operations and logistics	1) Productivity of forest operations (i.e. harvesting and thinning) 2) Investments in machinery 3) Changes in management operations	4) Logging costs 5) Safety issues 6) Mechanization level 7) Training activities
	Infrastructures	1) Forest accessibility 2) Forest roads / infrastructures 3) Damages on infrastructures	
Geomorphology	Channel dynamics	1) Alteration of riverine ecological niches 2) Watershed protection and risk mitigation	3) Increase in wood load 4)Transport of timber (suspended and bedload)

	Slope dynamics	1) Hillslope instabilities (i.e., Landslides, surficial erosion, debris flows…) 2) Large wood production and delivery 3) Sediment production and (delivery)	
Provision of ES	Provisioning services	1) Wood biomass 2) Game and wildlife 3) Biodiversity	
	Regulating services	1) Absorption of CO_2 2) Microclimate 3) Pests and disease control	4) Protection from natural hazards 5) Soil chemistry/ quality 6) Water quality/ composition
	Cultural services	1) Recreational activities 2) Tourism 3) Traditions	4) Aesthetic value of landscape
Institutional	Role of institutions		

		1) Change in policy/ legislation for forest management 2) Public technical assistance 3) State subsidies	
	Forest owners' perceptions	1) Environmental/ climate change issues 2) Future forest management practices 3) Self-perceptions (technical ability and income)	4) Risk management 5) Role of institutions and technical assistance
Social	Stakeholders' relations	1) Forest sectors stakeholders and institutions 2) Forest sectors stakeholders and community members 3) Within forest sector stakeholders 4) Forest sector and non-forest sector stakeholders	
	Social aspects	1) Community Engagement	

		2) Consequences at community level	
	Health and wellbeing	1) Forest owners' health 2) Public's wellbeing	
Economic	Labor market	1) Competences skills	
	Wood market and prices	1) Raw material availability 2) Wood market dynamics	3) Wood prices 4) Wood quality
	Forest related Markets	1) Wood sector value chain	
	Income variations	1) Private forest owners' income 2) Wood sector income 3) Non- forestry sector income	
	Banking and insurance sector		

Cultural	Cultural services	1) Knowledge production and academic investigation
	Landscape changes	1) Changes in forest landscape

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3 Paper II - Using high-frequency accelerometer to detect machine tilt

Alberto Cadei[1], Omar Mologni[2], Andrea Rosario Proto[3], Gaetano D'Anna[1], Stefano Grigolato[1]

[1]Department of Land, Environment,

Agriculture and Forestry, UniversitàDegliStudi di Padova

[2]Department of Forest Resources Management, Faculty of Forestry, The University of British Columbia

[3]Department of AGRARIA, Mediterranean University of Reggio Calabria

alberto.cadei@phd.unipd.it, omar.mologni@ubc.ca,andrea.proto@unirc.it, gaetano.danna@studenti.unipd.it, stefano.grigolato@unipd.it

3.1 Abstract

The use of full-mechanized harvesting systems is limited by terrain factors, such as very steep slopes and roughness terrain. Focusing on salvage logging conditions, forest operations are characterized by high costs and reduced productivity, as well as in terms of safety.

This work aims to identify and compare the relation between the machine tilt and ground slope and the effect in different harvesters and forwarders, based on the technology and type of machine. In particular, the machines involved in this study are a harvester and forwarder working in the specific condition of salvage logging in windthrow areas. High-frequency 3-axis accelerometers and a GNSS sensor were used to monitoring in continuous tilt and motion of the machines. From the position detected by the GNSS sensor, the ground slope was obtained.

The results report that the correlation between the machine tilt and ground slope dependson the type of the machine and technology. The high-frequency 3-axis accelerometer results are affordable to detect an accurate machine tilt showing the possibility to use the combination of different low-cost sensors to analyze the operation condition of forest machines in complex terrain.

Keywords: accelerometer, harvester, forwarder, windthrow, forest operations.

3.2 Introduction

Forests cover over 43% of the European Union land area (1.82 10^6 km^2)(Eurostat, 2020).Because of the increase of forest biotic and abiotic disturbances (e.g. bark beetle outbreaks, wildfires and wind storms) in the last years(Lindner et al., 2010; Seidl et al., 2014),the frequency of hazards to the operators when working in salvage logging conditions could increase(Sullman and Kirk, 2001a). When salvage logging is appropriate to be applied, the most suitable technological solutions are those based on fully mechanized systems as these guarantee high productivity and above all a lower risk for operators as they work exclusively on the machines(Enache et al., 2016; Kärhä et al., 2018a; Magagnotti et al., 2013).

Harvesting operations in steep terrain were characterized by chainsaw felling, followed by cable yarding extraction using choker-setters(Visser et al., 2014). According to Cavalli, (2015),specialized harvesting machines with special undercarriages and carriers can reach safely slope terrain up to 70% without external support.To improve stability in steep terrain and ensure the comfort of the operator, self-levelling of the cabin and crane have been introduced in forestry machines with tracked undercarriage (Jodłowski and Kalinowski, 2018). Wheeled machines use other solutions in order to change the position of the centre of gravity and increase stability. A typical solution is to increase the numbers of wheels and group in tandem (bogie) to reduce machine inclination and make easier to overcome small obstacles in the case of passive bogie (Berkett, 2012; Jodłowski and Kalinowski, 2018). Wheeled harvesting machines can also be equipped with additional hydraulic cylinders on the driven arms and operators can manually adjust the machine inclination ad overcome uneven terrain (e.g. ditches, stumps or stones) while tracked harvesting machines, in particularhalf-track,with independent suspension system canimprove the stability in rough or steep terrain(Mologni et al., 2016). A wheeled harvester, Valmet 911 Snake harvester, was adapted for the specific purpose of felling in steep terrain in (Berkett, 2012), where the standard wheels were replaced with four trapezoidal track. The improvement allows the machine to operate at slope limitation until 70%.

In the last few decades, the development of machine performance allowed the machine to extend the slope limitations until 75-85% (Visser and Stampfer, 2015). For example, the introduction of synchronized winch with wheels and self-leveling boom and cabin are the most important introduction that allowed the machine to expand the fully mechanized ground-based harvesting system (Cavalli and Amishev, 2019; Mologni et al., 2016; Visser and Stampfer, 2015).The introduction of these developments implied an increase in power and weight and, as a consequence, the impact on soil and stand conditions (Cambi et al., 2015; Garren et al., 2019). Larger-sized machines are necessary for storm damaged areas compared with normal conditions and operator training is also required to reduce risks for forest operators for example, harvesters in steep terrain and in salvage logging operations need to work in the direction of the main slope, in slope over 25%(CTBA, 2004).

The objectives of the present study are to identify the relation between the forest machine tilt and ground slope during salvage logging operationand to evaluate the efficiency of machines leveling in different terrain slopes.

3.3 Materials and methods

A total of five forest machines, three forwarders (F1, F2 and F3) and two harvesters (H1 and H2) were involved in this study (Table 3.1, Table 3.2).F3 used synchronized winch during timber extraction.

The data collection was based on a time and motion study through video recording using on-board digital video cameras (Drift®, Ghost-HD), as proposed by (Cadei et al., 2020; Grigolato et al., 2016). The machine position was collected using a GNSS receiver (Garmin® 64S) located inside the cabin. For better reception, the GNSS was integrated with an external magnetic antenna (Garmin® 25MCX) located outside the cabin. Both the video cameras and the GNSS receiver were powered with a 20,000 mAh power bank. Machine tilt was detected using an MSR® 145 high-frequency three-axis accelerometer installed on the chassis of the machines (data acquisition set at 25 Hz) and powered by its autonomous battery. A dedicated R code was developed in order to resample the different resolution of the DTM (1m and 2.5m) to the same resolution of 5 m cells adjacent using bilinear interpolation. Machine position collected from GNSS receiver was filtered applying a filter of 5 m for forwarders and 3 m for harvesters. Machine tilt was determined by the accelerometer data through a specific code developed in R studio software, with a resolution of 1 Hz. According to (Visser and Berkett, 2015), in order to reduce the effect of the machine vibration (e.g. short term extreme tilting),a running of five-points average (5s) was applied for estimate the machine tilt in percentage.Any delay time identified by the time and motion study was excluded from the dataset.

Table 3.1 *- Forwarder specifications*

Machine	Units	F1	F2	F3
Location	-	Passo Vezzena (TN)	Redagno di sopra (BZ)	Nevegal (BL)
Power	kW	136	129	210
Wheel number	n°	8	8	8
Steering angle	°	44	40	44
Weight empty	t	18.1	17	19.8
Load capacity	t	13	14	15
Tire size	-	710/45-26.5	710/45-26.5	710/45-26.5
Gross lifting torque	kNm	125	76	140
Maximum boom reach	m	10.0	8.4	10.0
Bogie	-	[1]PB+BS+DF	[2]BS+DF	[2]BS+DF
Cabin	-	[3]SL+R	-	-
Level crane	-	Yes	No	Yes

1-Portal bogie axle with balancing system and differential lock; 2-Balancing system with differential lock; 3-Self-levelling and rotating

Table 3.2 *- Harvester specifications*

Machine		H1	H2
Location	-	Redagno di sopra (BZ)	Passo Vezzena (TN)
Power	kW(hp)	240 (325)	193 (259)
Wheel number	n°	6	6
Steering angle	°	44	40
Weight	t	27.0	19.4
Front tire size	-	650/60-26.5	600/55-26.5
Rear tire size	-	700/70-34	600/65-34
Gross lifting torque	kNm	310.0	225,3
Maximum boom reach	m	11.5	10.0
Front axles	-	[1]BB+HPA +DL	[2]B+DL
Rear axle	-	[3]HC+DL	[4]HSA+DL
Cabin	-	[5]SL+R	[5]SL+R

1-Balanced bogie with hydraulic pendulum arms, mechanic differential lock; 2-Bogie and mechanic differential lock; 3-Axle equipped with hydraulic cylinder with differential lock; 4-Hydraulic swing axlewith differential lock; 5-Self-levelling and rotating

Table 3.3 *- Terrain slope classification*

Slope range (%)	**Designation**
<11	*Level*
11-20	*Gentle*
20-30	*Moderate*
30-35	*Steep 1*
35-40	*Steep 2*
40-50	*Steep 3*
>50	*Very steep*

Each machine was analysedin terms of tilt and the terrain slope at the same location of the machine. The terrain slope was classified according to theNational Terrain Classification NTC(Erasmus, 1994) (Table 3.3). The difference between estimated machine tilt and terrain slope from DTM in percentage (GST) was added to the machine dataset.

A two-way ANOVA was used to investigate the main effects of two independent factor variables (terrain slope classification and type of machine) and the effect of the interaction of the independent variables on the GST. For each machine, linear regression was used to test the relationship of the GST to the slope classification and type of machine, with the level of significance set to 0.05. Least-Square Means was used to evaluate the interaction between the independent variables as a prediction from the linear model.

3.4 Results and discussion

The total number of sample points was 188,323 for forwarder groped machines and 109,166sample pointsfor harvester grouped machines (Table 3.4). The difference between the machine tilt and ground slope was different for each machine. In particular, the H1 shows a positive average difference of 9%, while H2 shows a negative difference of 9%.In addition, the estimated machine tilt exceeded ground slope in all machines involved in this study, except for H2.

***Table 3.4** - Descriptive statistics of machine tilt and terrain slope classified per machine used*

		Machine tilt (%)			Terrain slope (%)			
Machine	N	5th percentile	Mean	95th percentile	5th percentile	Mean	95th percentile	Difference (%)
F1	35106	9.73	21.00	37.37	2.72	16.02	35.76	4.98
F2	76539	12.35	29.58	52.07	10.75	24.42	36.36	5.16
F3	76678	18.72	37.68	61.16	22.69	33.94	52.16	3.74
H1	44807	7.30	31.83	49.99	11.15	23.27	37.52	8.56
H2	64359	7.34	21.56	40.18	19.25	30.52	47.19	-8.89

Forwarder

The linear model shows statistical differences between forwarders and between GST and terrain slope classification among the same forwarders. F3 in level terrain report a low correlation with GST, with an adjusted R^2 explaining the 38% of the GST variation (F=5,690; $p < 0.01$).

As it is shown in Figure 3.1, F3 faced a wide range of ground slope. Furthermore, the effect of ground slope had lowered influence on machine tilt in very steep terrain (slope over 50%). The technology of the machine could explain the extreme ground slope faced during the forwarding operation of F3, and in particular, the use of the winch assist technology.

In Figure 3.2 is shown the effect of the terrain steepness on the forwarders tilt. Inlevel and gentle terrain (slope less than 20%), all the machines adjust and increase machine inclination, with respect to the terrain slope. Machine tilt was higher than ground slope, probably due to the presence of obstacles along the corridors (e.g. stumps or stones) and working elements(e.g. loading phases). In moderate terrain slope, the machines show different types of behavior, with GST of -4%, 7% and 15% respectively for F1, F2 and F3. Furthermore, GST of F1 in steep 1 terrain wassimilar to GST in moderate terrain. In steep 2 only F3 machine tilt was similar to ground slope (-1% GST). This means that the technology of F3 forwarder allowed to work in moderate terrain slopewithout particular positioning of the machine to reduce the machine tilt and increase the machine stability.In steep 3 terrain forwarders working with a GST from -8% to -14%. According to Figure 3.1, 479 data, recorded at 1 Hz, were detected for F1, while 2,009 and 10,240 data were recorded for F2 and F3. In very steep terrain, GST for F1 and F3 forwarders were respectively -30% and -28% while GST for F2 was -16%. Although F3 worked in very steep terrain for 13% of total time working (Figure 3.1), F3 adjusted the machine tilt of 28%, with respect to terrain slope.

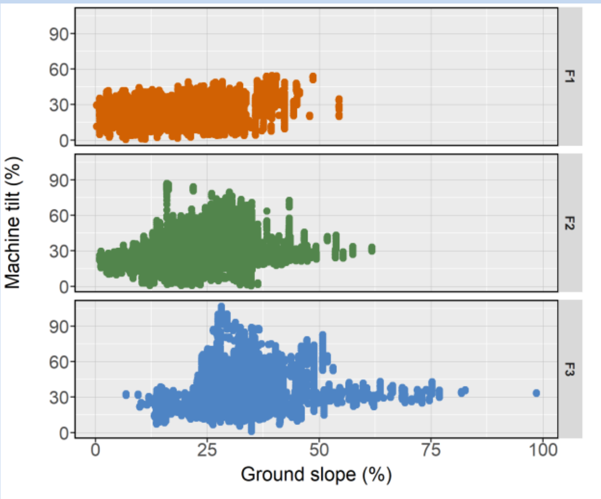

Figure 3.1 - Distribution of forwarder tilt and ground slope

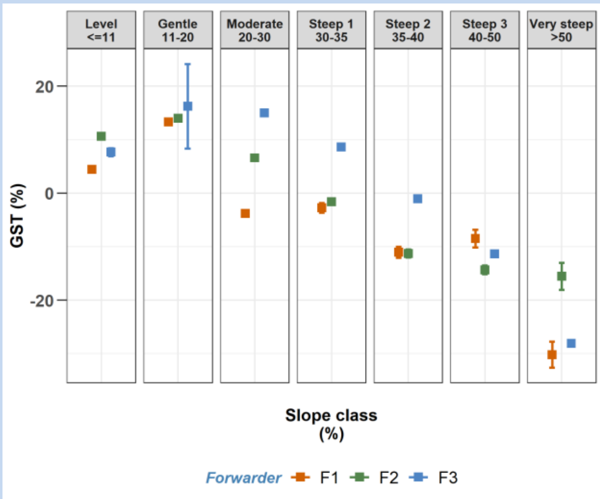

Figure 3.2 - Least square means of linear model

Harvester

The linear model shows statistical differences between harvesters and between GST and terrain slope classification. H2 in level terrain does not show a significant correlation with GST, due to the small amount of observation (48). However, the adjusted R^2 explains the 54% of the GST variation (F=9,863; $p < 0.01$).

Figure 3.4 shows the effect of the terrain steepness on the forwarder tilt. In level and moderate terrain, H1 working without manually machine levelling and machine tilt was slightly similar to the ground slope (GST 2% and -2% respectively). When the terrain slope increases up to 50%, H1 harvester, equipped with balanced bogie with hydraulic pendulum arms and axles equipped with hydraulic cylinder, was able toadjust the machine tilt, with the respect of ground slope, from a GST of -9% in steep 1 terrain, to -23% in steep 3 terrain. H2 harvester, equipped with bogie and hydraulic swing axle, working in steep terrain from ground slope of 30% to 50% with a GST from 2% to -3% respectively. Over 50% of ground slope, in very steep terrain H1 level the machine tilt of -37%, while H2 working with machine tilt lower than 24% compared to ground slope. As illustrated by Figure 3.3, H2 faced a wide range of ground slope, but over 50% of ground slope only 75 data recorded at 1 Hz were detected.

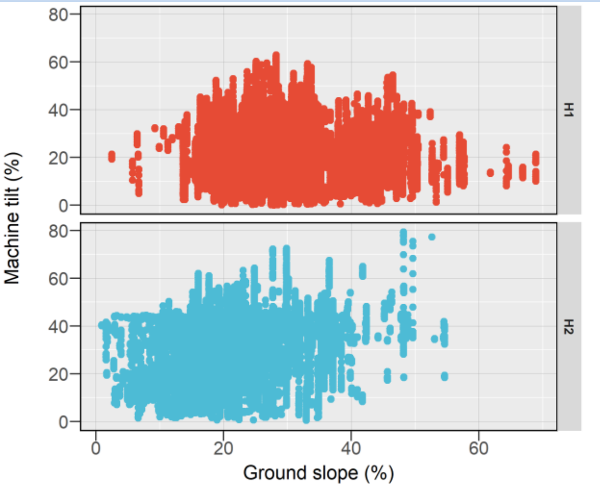

Figure 3.3 *- Distribution of harvester tilt and ground slope*

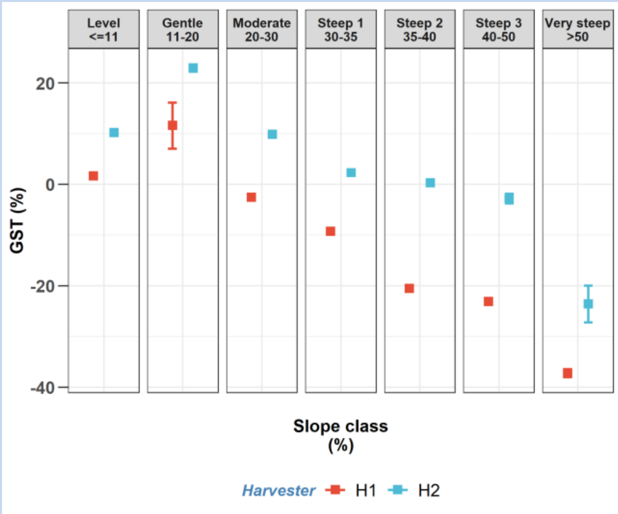

Figure 3.4 *- Least square means of linear model*

3.5 Conclusions

This study, based on three forwarders and two harvesters under real workingconditions, shows the effect of the ground slope on the machine tilt. Winch assisted forwarder equipped with a balancing system, differential lock and crane level can work in a wide range of ground slope and, over ground slope of 50% could reduce the machine tilt of 28%. Harvester equipped with balanced bogie with hydraulic pendulum arms and axles equipped with a hydraulic cylinder could reduce the machine tilt of 37% in slope over 50%.

However, the methodology adopted in this research, both in the field study and in the data analysis,shows great potential. This research needs to be done over a longer time period to collect a large amount of dataand, using GIS-based analysis,geo-referenced information could be used to identify critical harvesting areas and preferred corridors to operate safelyin steep terrain.

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4 Paper III – Forwarder Productivity in Salvage Logging Operations in Difficult Terrain

Alberto Cadei [1], Omar Mologni [2], Dominik Röser [2], Raffaele Cavalli [1] and Stefano Grigolato [1,*]

[1] Department of Land, Environment, Agriculture and Forestry, Università degli Studi di Padova, viale dell'Università 16, 35020 Legnaro, Padova, Italy; alberto.cadei@phd.unipd.it (A.C.); raffaele.cavalli@unipd.it (R.C.)
[2] Department of Forest Resources Management, Faculty of Forestry, The University of British Columbia, MainMall 2424, Vancouver, BC V6T 1Z4, Canada; omar.mologni@ubc.ca (O.M.); dominik.roeser@ubc.ca (D.R.)
* Correspondence: stefano.grigolato@unipd.it

4.1 Abstract

Large scale windthrow salvage logging is increasing in Central Europe because of the growth of severe atmospheric events due to global heating. Sustainable forest operations in these conditions are challenging in terms of both productivity performances and safety of the operations. Fully mechanized harvesting systems are the preferred solution on trafficable terrains and proper slopes. However, different work methods and logistic organization of the operations could largely change the overall performances. The study observed three harvesting sites based on fully mechanized cut-to-length systems and located in areas affected by the Vaia storm, which hit north-eastern Italy in October 2018. The objectives were to estimate forwarder productivity in salvage logging in difficult terrain and to identify significant variables affecting this productivity under real working conditions. Time and motion studies were carried out and covered 59.9 PMH_{15}, for a total of 101 working cycles, extracting a total volume of 1277 m^3 of timber. Average time consumption for each site was 38.7, 42.2, and 25.1 PMH_{15} with average productivity of 22.5, 18.5, and 29.4 m^3/PMH_{15}, respectively, for Sites A, B, and C. A total of seven explanatory variables significantly affected forwarder productivity. Average load volume, maximum machine inclination during loading, and number of logs positively affected the productivity. On the contrary, travel distance, load volume, maximum ground slope during moving and loading have a negative influence. With an average travel distance of 500 m, the productivity resulted 20.52, 16.31, and 23.03 m^3/PMH_{15}, respectively, for Sites A, B, and C. An increase of 200 m of travel distance causes a decrease in productivity of 6%.

Keywords: efficiency; steep terrain; cut-to-length; windthrow; Vaia storm

4.2 Introduction

Forest stands cover 43% of the European land and provide significant socioeconomic values through their ecosystem services. The European Commission confirms once again the fundamental role of forests in its strategic long-term vision for a prosperous, competitive, and climate neutral economy (EUROSTAT, 2019). This strategy can be seriously compromised due to the increment of forest disturbance in terms of frequency, severity, and extent mainly due to global heating (Seidl et al., 2014). Drought related losses, the increase in intensity and frequency of threats (e.g., wildfires and wind storms), and the subsequent exponential increase in biological risks (e.g., bark beetle outbreaks) are the most significant natural disturbances currently affecting the dynamics of forest ecosystems in Europe (Gardiner et al., 2013; Lindner et al., 2010) and the world in general (Johnstone et al., 2016). As a result, large post-disturbance management strategies focus on (i) active interventions or on (ii) passive management (Crouzeilles et al., 2017). Active intervention strategies focus on rapid post-disturbance harvest and recovery of the economic value of the forest (Müller et al., 2019) in order to decrease the risk of a rapid reduction of the timber value due to reductions in wood quality (Zimmermann et al., 2018), the risk of wildfires (Newton et al., 2006), and insect outbreaks (Nikolov et al., 2014).

A common post-disturbance management approach is salvage logging (Leverkus et al., 2018; Peterson and Leach, 2008) which consists of the widespread removal of damaged trees. Salvage logging benefits and drawbacks are widely discussed as it can have a negative effect on forests in terms of reducing biodiversity, increasing erosion, and reducing soil fertility (Leverkus et al., 2018). Some authors report that salvage logging interventions must be planned considering the site-specific characteristics (CTBA, 2004; Kramer et al., 2014). When salvage logging is appropriate to be applied, the most suitable technological solutions are those based on fully mechanized systems as these guarantee high productivity and above all a lower risk for operators as they work exclusively on the machines (Enache et al., 2016; Kärhä et al., 2018).

In complex terrain and in mountain areas, with a low density of forest roads, the use of fully mechanized systems in salvage logging operations is difficult. In these conditions, the main system remains the semi-mechanized system based on motor-manual felling with a chainsaw and timber extraction by cable yarders or skidders (Bodaghi et al., 2018). In recent years, even the fully mechanized system based on the combined use of harvesters and forwarders has been spreading with the use of heavier and more suitable machines for working on steep and trafficable terrain (Mologni et al., 2016; Visser and Stampfer, 2015). Currently, harvesters with independently suspended tracks or wheels mounted on hydraulically driven arms or forwarders with heavy-duty portal bogie axles with balancing system and self-levelling cabins, and fitted with a synchronized winch to improve traction are the main developments introduced in ground-based harvesting system in the last years to operate in complex and steep terrain up to 75%–85% slope (Visser and Stampfer, 2015). Forwarders are machines typically used in fully mechanized cut-to-length (CTL) timber harvesting with the aim to extract timber from the forest to the landing sites (Cambi et al., 2017;

Tiernan et al., 2004). Due to the lower risk for forest operators, lower harvesting costs, and higher productivity (Proto et al., 2018), fully mechanized CTL harvesting systems are commonly applied in mountain regions in order to harvest damaged trees from the forests.

Forwarder productivity has been widely studied in Europe. The main factors that affect forwarder productivity are related to forest stand and ground conditions such as density of the trees, volume of payload, number of logs extracted, number of log assortments, average log volume, extraction distances and direction of wood extraction, terrain slope, operator's experience (Holzfeind et al., 2018; Nurminen et al., 2006; Proto et al., 2018; Tiernan et al., 2004). Typically, slope and extraction distance have a negative influence on productivity while volume of payload has a positive influence (Stankić et al., 2012). According to Ghaffarian et al. (Ghaffarian et al., 2007) the extraction distance has a negative influence on productivity, while the increase of load volume and downhill slope have a positive influence on productivity. Payload should be positively related to productivity, Eriksson and Lindroos (Eriksson and Lindroos, 2014) find that the productivity between forwarders with different payloads decreased with extraction distance, both in final felling and thinning. Obviously, larger machines require a higher investment but, on the other hand, are expected to have higher productivity and a lower cost per m^3 (Jiroušek et al., 2007). Additionally, type of operation and stand affected forwarder productivity, for example In Ireland, in clearcut and thinned working areas forwarder productivity could range from 13.57 to 27.25 m^3/PMH and from 7.28 to 13.92 m^3/PMH, respectively (Tiernan et al., 2004). Previous studies mentioned productivity related to ordinary harvesting conditions or salvage logging operation in gentle terrain, while there is a lack of knowledge about the productivity of forwarders in non-ordinary conditions, such as salvage logging, in complex and steep terrain. For example, in Finland cutting costs in salvage logging operations were estimated to be about 35%–64% higher than ordinary clearcutting and the logging costs were 10%–30% higher than normal standing stems (Bodaghi et al., 2018; Kärhä et al., 2018). Although harvester productivity in salvage logging operations are lower, compared with normal clearcutting, Bergkvist (Bergkvist, 2005) does not detect any significant difference in forwarder productivity in salvage logging operations compared to normal clearcutting. This paper aims to partially fill the lack of knowledge of forwarder productivity in salvage logging operation in difficult terrain. The specific objectives of the paper are (i) to estimate time consumption and evaluate forwarder productivity in salvage logging in difficult terrain and (ii) to identify the most significant variables affecting productivity of forwarding operation in salvage logging operations in difficult terrain and under real working conditions.

4.3 Materials and Methods

4.3.1 Case Studies

The study was conducted in 2019 in the Italian Alps in the forest area affected by windthrow caused by Vaia storm that occurred at the end of October 2018 (Chirici et al., 2019; Motta et al., 2018). Data were collected in three different sites, respectively, located in Levico Terme (TN), Aldino (BZ), and Belluno (BL) (Site A, Site B, and Site C) (Figure 4.1) (Table 4.1).

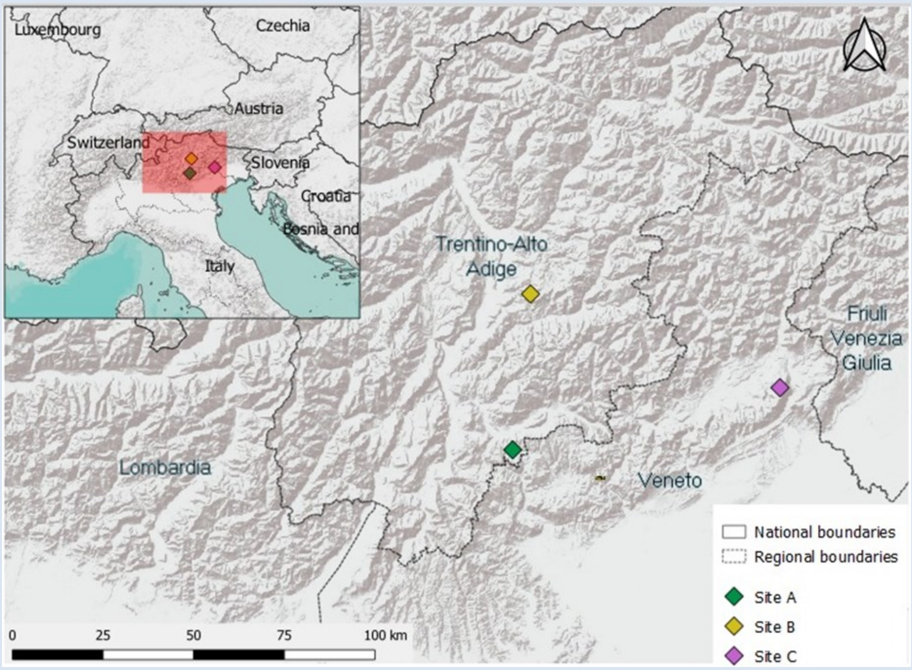

Figure 4.1 *- Location of the different working areas*

Site A was composed of a mixed even-aged stand with spruce (*Picea abies*) and silver fir (*Abies alba*) located at an average altitude of 1460 m a.s.l. The damaged area was estimated to be about 65% of the total stand area. Site B was composed by a mixed even-aged stand with spruce, silver fir, and European larch (*Larix decidua*) located at an average altitude of 1600 m a.s.l. In this site, the damaged area was estimated to be about 100% of the stand. Site C was composed of a mixed uneven-aged stand with spruce and European larch, with different broad-leaved species such as beech (*Fagus sylvatica*), maple (*Acer pseudoplatanus*), and birch (*Betula pendula*) mixed in. Overall, the broad-leaf volume did not exceed 6% of the total estimated volume. Site C was located at an average altitude of 1300 m a.s.l. with an estimated damaged area of 40% of the total stand.

***Table 4.1** - Stand description and characteristics of damage for the three different working areas*

	Site A	Site B	Site C
Location	Passo Vezzena	Redagno di sopra	Nevegal
Province	Trento	Bolzano	Belluno
Elevation (m a.s.l.)	1460	1600	1300
Total area (ha)	20	30.5	60.48
Damaged area (%)	65	100	40
Estimated damaged wood (m^3)	3500	10,000	25,000
Average slope (%)	17	24	33
Species (% of volume)			
Abies alba	35	30	-
Picea abies	65	60	73
Larix decidua	-	10	21
Broad leaved	-	-	6

4.3.2 Machine Details

According to Brunberg (Brunberg, 2004), different forwarders can be grouped by loading capacity from light forwarders (up to 10 t), medium forwarders (10–14 t) to heavy forwarders (over 14 t). The forwarders used in the three different sites included two medium-size forwarders, a John Deere 1210 E (Site A) and an Ecolog 574 B (Site B), with, respectively, 136 and 129 kW engine power, and one heavy forwarder (Site C), Ponsse Buffalo, with 210 kW engine power. Both the John Deere 1210 E and Ponsse Buffalo were equipped with a synchronized winch, but during field activities the winch was only used in Site C. Details of the machines are reported in Table 2.

Table 4.2 *- Details of the machines used*

Case Studies		**Site A**	**Site B**	**Site C**
Model		John Deere 1210 E	Ecolog 574 B	Ponsse Buffalo
Engine	-	John Deere 6068	CAT 3065 E	Mercedes-Benz MTU OM936
Power	kW (hp)	136 (183)	129 (173)	210 (286)
Ground clearance	mm	605	650	680
Cylinders	n°	6	6	6
Wheel number	n°	8	8	8
Steering angle	°	44	40	44
Weight empty	t	18.1	17.0	19.8
Load capacity	t	13	14	15
Tire size	-	710/45-26,5	710/45-26,5	710/45-26,5
Boom crane model	-	CF7	Loglift 83	Ponsse K 90+ M
Gross lifting torque	kNm	125	76	140
Maximum boom reach	m	10.0	8.4	10.0

4.3.3 Data Collection

The data collection was based on a time and motion study through video recording using on-board digital video cameras (Drift®, Ghost-HD). The acquisition rate was set at 720 ppm with 30 frame/s and a field of view of 170°, as also proposed in similar studies (Grigolato et al., 2016; Holzfeind et al., 2018; Holzleitner et al., 2018; Mologni et al., 2018). As proposed by Mologni et al. (Mologni et al., 2018), in order to estimate forwarder load volume, high-resolution photos were taken of each load both from the back and laterally. Photos were then corrected in terms of perspective correction using GIMP® software (GNU Image Manipulation Program) to reduce minimal distortions and scaled by AutoCAD® according to the measured forwarder bunk width.

The machine position was collected using a GNSS receiver (Garmin® 64S) located inside the cabin. For better reception, the GNSS was integrated with an external magnetic antenna (Garmin® 25MCX) located outside the cabin. Both the video cameras and the GNSS receiver were powered with a 20,000 mAh power bank. Machine inclination was detected using a high-frequency three-axis accelerometer installed on the chassis of the forwarder (data acquisition set at 25 Hz) and powered by its autonomous battery. Terrain slope was estimated using QGIS® software in order to compute the slope calculation from the digital elevation model (DTM), in all the sites, a DTM with a resolution of 1 m was available.

A dedicated R code was developed to analyze the data. The extraction distance was estimated for each work cycle using the GNSS data and applying a position filter of 5 m. The machine inclination was determined by the accelerometer data through a specific code developed in R software, with a resolution of 1 Hz.

4.3.4 Time and Motion Study and Work Phase Classification

A time-motion study was carried out through a stop-watch method which was based on video analysis and was set to time units of 1 s (sexagesimal). As common in time-study, observed time was separated into work time (WT) and non-work time (NT) (Björheden, 1991). WT included the productive work time, the related main working time, and the complementary working time, while NT was separated into mechanical, operational, and personal delays as proposed by different authors (Proto et al., 2018; Spinelli and Visser, 2008).

Forwarder operations from the felling site to the landing site are characterized by a cyclic work (namely work cycle or also turn) which can be divided into the following work elements:

travel empty: movement from the landing site (empty) to the loading site. Starts from the movement of the wheels, ends with the swing of the boom crane (priority 2);

loading: starts with the swing of the boom crane at the loading site, ends when the boom crane stops to swing (priority 1);

- driving while loading: movement from different loading sites, starts from the movement of the wheels at loading site after a loading working element; ends when the boom crane starts to swing (priority 2);
- travel loaded: movement from the loading site to landing site; starts with the movement of the wheels, ends when the boom crane starts to swing (priority 2);
- unloading: when the boom crane unloads the logs at landing site; starts when the wheels stop and the boom crane starts to swing, end when the boom crane stops to swing and wheels start to move at the end of the unloading phase (priority 1);

delay time: included delays up to 15 min.

The time-motion study analyzed the working time according to the previous work element classification. If work elements were overlapping, the element with the highest priority (lower number) was recorded as also proposed by Manner et al. (Manner et al., 2013).

4.3.5 Independent Variables

A total of 13 explanatory variables for productivity model were investigated (Table 4.3). For each cycle, the following independent variables were defined: total travel distance and average speed (derived by the data collected on the machine position), maximum and average machine inclination (derived by the data recorded through a three-axis accelerometer); maximum and average machine inclination (derived by GIS analysis), load volume (over bark), and total log number (both derived by the analysis of the photos of each forwarder loaded volume). In the present study, the inclination of the machine was calculated as the resulting inclination between the roll and the pitch of the machine itself. This choice was motivated by the fact that the forwarders work continuously in conditions such that they were inclined both horizontally and sideways. For this reason, the inclination resulting from the roll and pitch represents a unique absolute value of inclination of the machine.

The average ground slope, average machine inclination, maximum ground slope, and the maximum machine inclination were assigned in relation to the following work elements: moving (including travel empty and travel loaded) and loading time. The average speed per cycle (speed) was estimated dividing the travel distance for each cycle for the respective moving time (sum of travel empty, drive while loading, and travel loaded for each cycle).

Table 4.3 *- Description of the variables tested in the time models*

Definitions	Variable
Average ground slope during moving time	AGS_M
Average ground slope during loading time	AGS_L
Average log volume	ALV
Average machine inclination during moving time	AMI_M
Average machine inclination during loading time	AMI_L
Load volume	LV
Maximum ground slope during moving time	MGS_M
Maximum ground slope during loading time	MGS_L
Maximum machine inclination during moving time	MMI_M
Maximum machine inclination during loading time	MMI_L
Number of logs	NL
Speed	S
Travel distance	TD

4.3.6 Productivity Model and Statistical Analysis

The productivity model, considering delay-free productive machine hour (PMH_0) was defined using all the data from Sites A, B, and C with the work cycle set as the observational unit. Time-consumption models were divided into the following different equations:

1. Time moving (TM): the sum of travel empty, travel while loading, and travel loaded in minutes (Equation (1));
2. Time loading (TL): loading time in minutes (Equation (2));
3. Time unloading (TU): unloading time in minutes (Equation (3)).

To convert the delay-free productive machine hour (PMH_0) into productivity machine hour including delays shorter than 15 min (PMH_{15}), a correction factor *k* should be applied. The *k* factor can be derived from the study observations if the study is based on a long observation time. In the present study, the observation time is not long enough, and it is suggested to derive the *k* factors from the literature. In the present study, as proposed by Holzleitner et al. (Holzleitner et al., 2018), a correction factor of 0.3 was used as indicated by Stampfer (Stampfer, 1999). In order to estimate total time consumption per cycle (TTC), including delays less than 15 min and expressed in hours, the sum of TM, TL, and TU (Equations (1)–(3)), multiplied by *k* factor, were divided by 60 (Equation (4)).

As proposed by Tiernan et al. (D Tiernan et al., 2004), predicted productivity can be estimated by the total time consumption (TTC) for extracting know load volume (LV) as expressed in Equation (5).

$$TM = f(AGS_M, ALV, AMI_M, LV, MGS_M, MMI_M, NL, TD, S) \quad (1)$$

$$TL = f(AGS_L, ALV, AMI_L, LV, MGS_L, MMI_L, NL) \quad (2)$$

$$TU = f(ALV, LV, NL) \quad (3)$$

$$TTC\ (PMH_{15}) = \frac{60}{(1+k)*(TM+TL+TU)} \quad (4)$$

$$Productivity\ (\frac{m^3}{PMH_{15}}) = \frac{LV}{TTC} \quad (5)$$

Due to the diversity of the site areas (e.g., working conditions, operator's experience, type and technology of the forwarders) the site variable was assumed as random factor and the regression analysis was based on random-intercept linear mixed effect models (Bates et al., 2015a; Hiesl and Benjamin, 2013).

As indicate by Hiesl et al. (Hiesl and Benjamin, 2013), the random intercept included the different influences of the operator, machine, and site conditions at each location. Random intercept mixed effect models consider this different combination of operator, machine, and site at each location as unique. Random slope of the regression was also tested for the significance as appropriate. A likelihood ratio test was used to evaluate the significance of the individual variables; the significance level of the statistical analysis was set to 0.05. In order to analyze statistical assumptions, residuals were checked using residual plot distributions. In the case of non-normal distribution of the residual, logarithmic and square root transformations were tested on both response variables and explanatory continuous variables. The goodness of fit of linear mixed effect models was tested through the coefficient of determination (R^2_{LR}) proposed by Magee (Magee, 1990) and based on likelihood ratio joint significance.

4.4 Results

Total time studies covered 57.90 PMH_{15}, divided into 10.41 PMH_{15} in Site A, 23.64 PMH_{15} in Site B, and 23.85 PMH_{15} in Site C. Field activities covered 10 days, three days in both Site A and Site B, and four days in Site C. Within this time, the forwarders completed 101 working cycles, 16 in Site A, 33 in Site B, and 52 in Site C. Total extracted timber volume for all sites was 1277 m^3, resulting in 4284 logs. About 223 m^3 and 884 logs were extracted in Site A, 417 m^3 and 1385 logs in Site B, 637 m^3 and 2015 logs in Site C. Time consumption was distributed as shown in Figure 4.2. The mean time consumption per cycle was 38.7, 42.2, and 25.1 PMH_{15}, respectively for Sites A, B, and C.

Average productivity was 22.5 m^3/PMH_{15} in Site A, 18.5 m^3/PMH_{15} in Site B, and 29.4 m^3/PMH_{15} in Site C. As shown in Figure 4.3, especially in Site C there was higher variability, due to the different types of assortments extracted and the use of the winch on the forwarder.

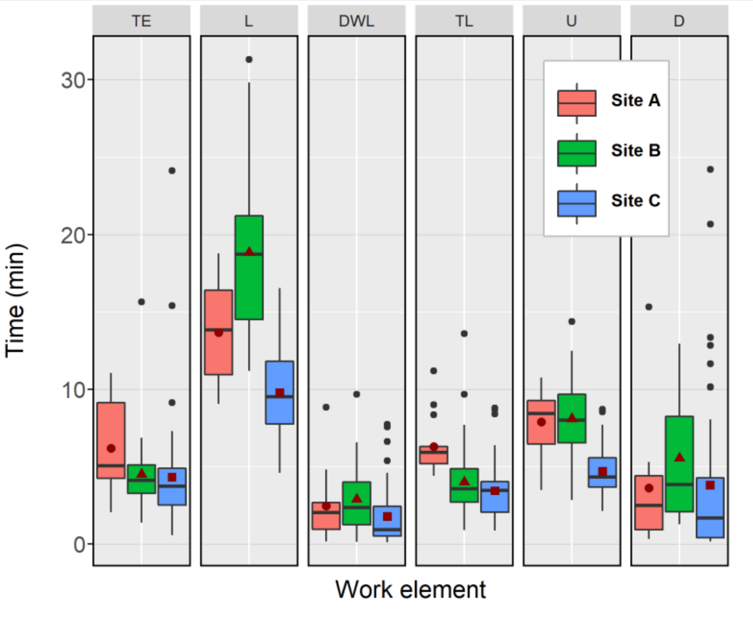

Figure 4.2 *- Time consumption of work element for different site where TE is travel-empty, L is loading, DWL is drive while loading, TL is travel loaded, U is unloading, and D is delay. The boxes include the variability of the data between the 25th and the 75th percentiles. The horizontal black line represents the median while the circle, triangle pointing upwards, and square in dark red represent the mean*

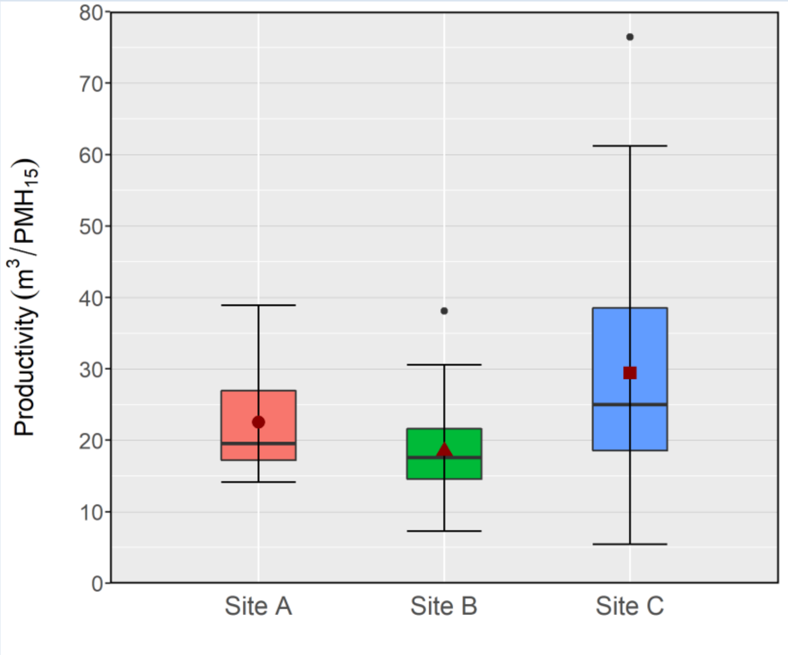

Figure 4.3 *- Variability of forwarder productivity for the three sites with work cycle as observational unit. The boxes include the variability of the data between the 25th and the 75th percentiles. The horizontal black line represents the median while the circle, triangle pointing upwards, and square in dark red represent the mean.*

Higher mean time consumption per cycle was recorded in Site B, probably due to the highest mean ground slope and machine inclination (Table 4.4). The longest work element was loading phase for all sites. In particular, loading phase in Site B was higher than Sites A and C, probably due to the highest average number of logs, average load volume, and corresponding average log volume (Table 4.4). Furthermore, the forwarder used in Site B was a medium-size machine with lower power compared with the others and not equipped with self-levelling cabin, and the working area was completely covered by windthrows. Loading time was lower in Site C, where the average number of logs extracted was lower and the corresponding average log volume was higher.

Table 4.4 *- Descriptive statistics for the independent variables considered in the statistical analysis*

Variables	Unit	Site A Min	Site A Average	Site A Max	Site B Min	Site B Average	Site B Max	Site C Min	Site C Average	Site C Max
AGS_M	%	11.2	15.7	22.8	9.5	24.7	32.7	17.6	31.2	43.9
AGS_L	%	11.5	23.1	36.1	9.5	25.1	34.7	19.3	34.1	72.6
ALV	m^3	0.1	0.34	0.67	0.15	0.33	0.81	0.11	0.36	0.81
AMI_M	%	18.0	22.6	26.5	21.6	30.7	38.4	19.9	39.6	57.6
AMI_L	%	15.0	21.5	39.7	7.5	33.4	60.1	17.0	41.7	65.0
LV		10.1	13.9	19.6	6.3	12.7	18.7	1.9	12.2	24.9
MGS_M	%	26.9	47.4	85.9	20.9	43.3	68.9	26.2	45.3	85.5
MGS_L	%	24.3	43.9	85.9	19.2	31.9	56.7	24.8	40.4	94.8
MMI_M	%	20.2	43.6	57.3	43.0	66.4	88.6	38.8	70.0	96.2
MMI_L	%	20.3	38.0	58.8	20.5	56.9	90.4	31.6	65.6	95.6
NL	n°	26	55.0	104	23	42	65	11	38	86
S	$m\ s^{-1}$	1	1.3	1.6	0.4	0.8	1.3	0.3	0.8	1.7
TD	m	606	1181	1834	217	557	1457	41	434	2221

Note: AGS_M: average ground slope during moving; AGS_L: average ground slope during loading; ALV: average log volume; AMI_M: average machine inclination during moving; AMI_L: average machine inclination during loading; LV: load volume (m^3 are over bark); MGS_M: maximum ground slope during moving; MGS_L: maximum ground slope during loading; MMI_M: maximum machine inclination during moving; MMI_L: maximum machine inclination during loading; NL: number of logs; S: speed; TD: travel distance.

In order to detect and estimate the variables affecting forwarder productivity in salvage logging operations, the variables in Table 4.5 were used in the linear mixed effect models. The highest speed (S) was registered in Site A, where the respective travel distance was the highest and the average ground slope and machine inclination during moving and loading were lower.

Productivity Equations

The aim of this study was to improve the understanding of time consumption and forwarder productivity salvage logging operations and in difficult terrain, and not to compare the productivity among different sites. Response variables of the time moving (TM) (Table 4.5) were the average log volume (ALV), max ground slope (MGS_M), and travel distance (TD). ALV had a negative influence on the time moving, while MGS_M and TD had a positive influence on the time moving. Therefore, with an increase of ALV, time moving decreased. On the contrary, with an increase of MGS_M or TD, time moving increased.

Table 4.5 *- Explanatory variables of fixed effect in time moving (TM), time loading (TL), and time unloading (TU) (Log: the logarithmic transformation of the variable).*

Equation	Response variable	Coefficient	Estim.	SE	*t* value	*p* value
1 (TM)	Time moving (min)	ALV (m^3)	−4.151	1.28	−3.240	0.010
		MGS_M (%)	0.075	0.02	3.764	<0.001
2 (TL)	Log Time loading (min)	ALV (m^3)	−1.004	0.134	−7.516	<0.001
		MMI_L (%)	−0.006	0.001	−4.344	<0.001
		MGS_L (%)	0.005	0.002	3.192	0.002
3 (TU)	Log Time unloading (min)	LV (m^3)	0.041	0.007	5.965	<0.001
		NL (n°)	−0.004	0.002	−2.324	0.020

Note: ALV: average log volume; MGS_M: maximum machine ground slope; MMI_L: maximum machine inclination during loading; MGS_L: maximum ground slope during loading; LV: load volume (over bark); NL: number of logs.

As the slope of explanatory variables, in particular ALV and TD, would seem to vary among the site areas, both random intercept and slope were tested. The highest significance of Equation (1) (TM) was reached using distance as random slope (Table 4.6).

Table 4.6 *- Explanatory variable of random effect using in Equation (1) TM*

Equation	Coefficient	SD	Variance	*p* value
1 (TM)	TD	0.002	−228.5	<0.001

Note: TD: Travel distance.

The estimate of the random slope of the TD was 0.07 for Site A, 0.09 for Site B, and 0.01 for Site C. The random slope showed a significant influence between the equations (*p* value 0.014). Equation (1) (TM) (Table 4.7) explains over 75% of the variability.

The variables that significantly affect time loading (TL–Equation (2)) (Table 4.5) were the average log volume (ALV), maximum machine inclination (MMI_L), and maximum ground slope (MGS_L). Equation (2) explains over 40% of the variability, where ALV and MMI_L had a negative influence on the time loading while MGS_L had a positive effect on time loading. Anyway, the effect of MMI_L and of MGS_L on the loading operation is marginal if it is compared to the higher effect of the ALV. The presence of single obstacles along the corridors, such as stumps or large stones, can affect in some cases the position of the machine during the loading operation as well as the maximum ground slope along the extraction trail.

Equation (3) related to time unloading (TM) (Table 4.7) explains the 32% of variability, variables that significantly affect time unloading were load volume (LV) and number of logs (NL). LV had a positive influence on time unloading while NL had a negative influence on time unloading (Table 4.5).

Table 4.7 *- Random intercepts and goodness of fit of the linear mixed-effect models.*

Equation	N	Variance	SD	L_M	L_0	R^2_{LR}
1 (TM)	101	4.118	2.029	−228.49	−295.50	0.735
2 (TL)	101	0.07	0.268	6.389	−19.56	0.402

3 (TU)	101	0.06	0.249	−13.12	−32.64	0.321

Note: N: number of observations; L_M: log likelihoods of the model; L_0: log likelihoods of the intercept; R^2_{LR}: coefficient of determination proposed by Magee (Magee, 1990).

Figure 4.4 shows the effect of the average log volume and travel distance on productivity, according to the different equations applied. In Sites A and C, forwarder productivity results were slightly similar over 600 m of travel distance. Furthermore, over 800 m travel distance, with an ALV of 0.3 and 0.35 m^3 in Site A and an ALV of 0.25 and 0.30 m^3 in Site C, Site A and Site C productivity overlapped.

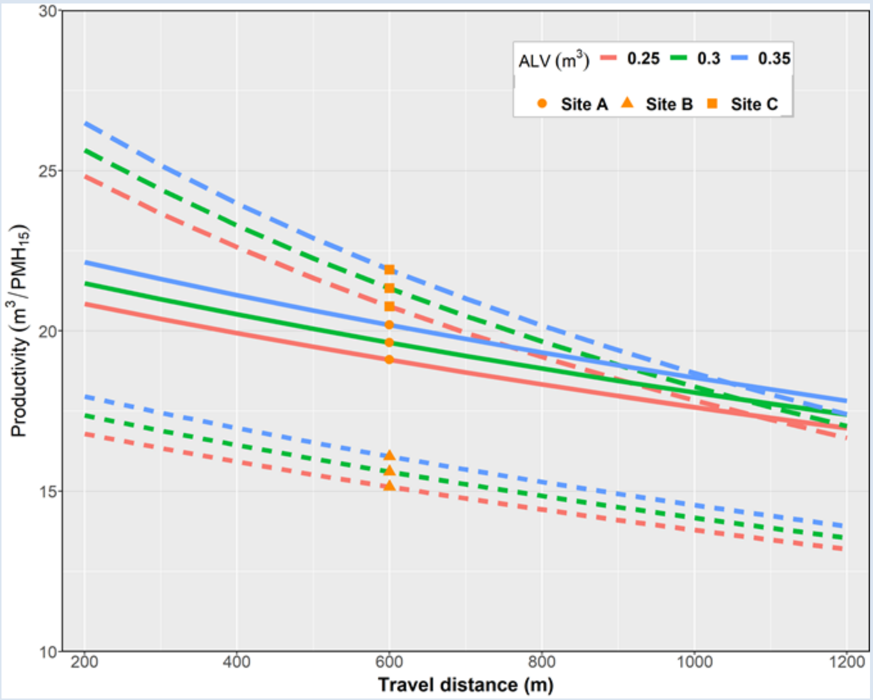

Figure 4.4 *- Predicted forwarder productivity (m^3/PMH_{15}) in relation to the total travel distance with ALV (average log volume) of 0.25, 0.3, and 0.35 m^3. The models, based on linear mixed effect models, consider site variables as random factor. Triangle pointing upwards, circles, and squares represent, respectively, Sites A, B, and C*

4.5 Discussions

In the current study related to salvage logging operations in difficult terrain, the predicted productivity of forwarder shows a range from 14.4 to 20.5 m^3/PMH_{15} for a medium-size machine (10–14 t) and from 18.8 to 23.0 m^3/PMH_{15} for a heavy-size machine (over 14 t) with an extraction distance between 250 and 500 m.

Forwarder productivity is generally affected mainly by load volume and the extraction distance, as it is clearly reported in (Eriksson and Lindroos, 2014; Ghaffarian et al., 2007; D Tiernan et al., 2004). Additionally, in the current study in salvage logging condition, the extraction distance has a significant influence on forwarder productivity.

The predicted productivity, with a total travel distance of 500 m resulted in 20.5, 16.3, 23.0 m^3/PMH_{15}, respectively, for the forwarder operating in Sites A, B, and C. Overall, an increase of 200 m of total travel distance reduces the productivity by 6% on average.

For what it concerns the lower productivity of the forwarder reported in Site B, this could be affected by the type of machine (medium-size forwarder without self-levelling and rotating cabin) as well as by the lower experience of the operator as was also identified by (Brewer et al., 2018; Malinen et al., 2018; Nurminen et al., 2006). The forwarder operator working at Site B, in fact, had six months experience, while the operator on forwarder operating in Site A had 10 years and the operator on the forwarder operating in Site C had about two years of experience.

In this study, the combination between machine characteristics, machine operator's experience, as well site conditions were unique at each location. As a consequence, the adaptation of the linear mixed-effect model was used to define a random intercept representing the combination of the previous variables as also suggested for a similar case by (Hiesl and Benjamin, 2013).

Figure 4.5 compares (up to a maximum travel distance of 1200 m) the productivity model of the present study with the productivity models gathered from other references. In this case, to keep consistent the m^3/PMH_{15} between the different productivity models a delay factor (*k*) of 0.3 (Stampfer, 1999) was applied.

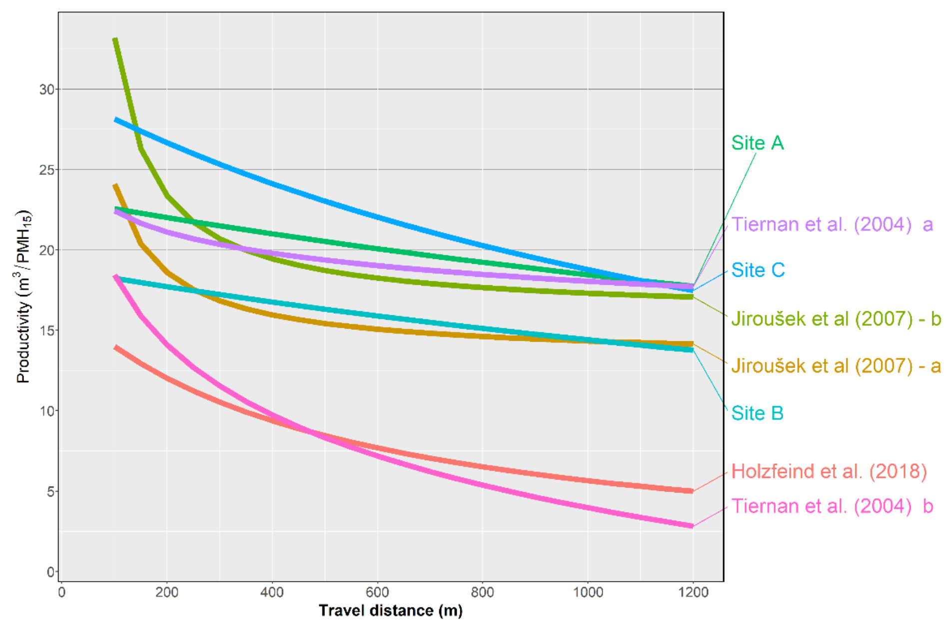

Figure 4.5 *- Comparison of variation of forwarder productivity with total travel distance with previous publications*

In Sites A and C, the productivity of the forwarders was slightly similar to Tiernan et al. (2004) (model a) (D Tiernan et al., 2004), where the model explains the effect of travel distance on the productivity in easy terrain conditions (with even ground conditions and terrain slopes less than 10%) in clearcutting operations. Tiernan et al. (2004) (model b) (D Tiernan et al., 2004) shows the effect of the travel distance on forwarder productivity in difficult terrain conditions (with poor ground conditions and ground slope greater than 10%) during clearcutting operations. The average extraction distance ranges from 100 to 700 m estimated by Tiernan et al. (D Tiernan et al., 2004). In order to compare extraction distances estimated by Tiernan et al. (D Tiernan et al., 2004) (estimated as half of the travel distance per cycle) with the travel distance in this study (estimated as travel distance per cycle) the extraction distance estimated by Tiernan et al. (D Tiernan et al., 2004) is doubled. In addition, Tiernan et al. (D Tiernan et al., 2004) models to predict forwarder productivity in clearcut areas includes a total of 56 cycles. Jiroušek et al. (Jiroušek et al., 2007) reports two models (a and b) explaining, respectively, the effect of travel distance on the productivity with medium and heavy forwarders, where the medium forwarder was a forwarder with a payload from 10 to 12 t and the heavy forwarder was a forwarder with a payload higher than 12 t. The productivity of medium forwarder is similar to medium forwarder of Site B, while the productivity of the heavy forwarder compares well with the Site A medium forwarder over 200 m of travel distance.

Holzfeind et al. (Holzfeind et al., 2018) estimate productivity of 16 m^3/PMH_{15} for a John Deere 1110E medium-size winch assist forwarder with an average log volume of 0.22 m^3, an average extraction distance of 111 m, an average extraction slope of 29.2%, and a load volume of 9.25 m^3, where the average extraction distance was estimated as the distance from the closest loading point to the unloading point. In the current study, the heavy winch assist forwarder operating in Site C reported a higher productivity than (Proto et al., 2018). This is probably due to larger size of the machine as well the higher concentration of logs along the corridors as is common on salvage logging operations. This circumstance is consistent with (Bergkvist, 2005), reporting that the forwarder productivity is similar to the productivity in normal clearcuts.

4.6 Conclusions

The present study analyzed and evaluated the productivity of forwarders in salvage logging operations and identified the most significant variables affecting productivity in difficult terrain. This study reports that the productivity in salvage logging in difficult terrain with a heavy forwarder (Site C) is in line with forwarder productivity in easy conditions during clearcut operations. Predicted productivities are positively affected by average load volume, maximum machine inclination during loading, and number of logs. On the contrary, travel distance and maximum ground slope have a strong negative influence on productivity. The results of the models confirm the effect of the travel distance on forwarder productivity and could be used in the future to plan and optimize road distribution in order to optimize forwarding efficiency in salvage logging operations based on CTL systems. In particular, the results partially cover the lack of knowledge of forwarder productivity in salvage logging operations and represent the first study of forwarder productivity in large scale windthrow and in difficult terrain in the Alps. In addition, the results quantified the variation of forwarder productivity with average log volume, ground slope, travel distance, machine inclination, load volume, and number of logs. In terms of road distribution, the position of these roads should be such as to minimize the extent of forwarding that may be economical. Although in this study machine inclination significantly affected forwarding productivity, higher machine inclination could also affect mechanical part of the machines.

However, forwarder productivity could be also related to harvester productivity and efficiency during salvage logging operation in difficult terrain. In order to better understand efficiency and the productivity of a CTL systems in non-ordinary conditions, such as salvage logging operations, further investigations involving harvester and forwarder operations are necessary.

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5 Paper IV – Energy efficiency of a hybrid cable yarding system: a case study in the North-Eastern Italian Alps under real working conditions

Alberto Cadei[1], Omar Mologni[2], Luca Marchi[1], Francesco Sforza[1], Dominik Röser[2], Raffaele Cavalli[1], Stefano Grigolato[1*]

[1] Department of Land, Environment, Agriculture and Forestry, Università degli Studi di Padova, Viale dell'Università 16, 35020 Legnaro, Padova, Italy; alberto.cadei@phd.unipd.it (A.C.); luca.marchi@unipd.it (L.M.); francesco.sfroza@unipd.it (F.S.); raffaele.cavalli@unipd.it (R.C.);

[2] Department of Forest Resources Management, Faculty of Forestry, The University of British Columbia, MainMall 2424, Vancouver, BC V6T 1Z4, Canada; omar.mologni@ubc.ca (O.M.); dominik.roeser@ubc.ca (D.R.)

*Corresponding author: stefano.grigolato@unipd.it (S.G.);

5.1 Abstract

In order to reduce greenhouse gas emissions, low emission or zero-emission technologies have been applied to light and heavy-duty vehicles, adopting electric propulsion systems and battery energy storage. Hybrid cable yarders and electrical slack-pulling carriages could represent an opportunity to increase the energy efficiency of forestry operations leading to lower impact timber harvesting and economic savings due to reduced fuel consumption. However, given the limited experience with hybrid-electric systems applied to cable yarding operations, these assumptions remain uncertain. This study assessed an uphill cable yarding operation using a hybrid cable yarder and an active slack-pulling electric power carriage over 30 net working days. A total of 915 work cycles on four different cable lines were analysed. Long-term monitoring using Can-BUS data and direct field observations were used to evaluate the net energy consumption, Net EC (kWh), total energy efficiency, TEF (%), and fuel consumption per unit of timber extracted (l/m^3). The electric-hybrid system, with the use of a 700 V supercapacitor to store the recovered energy, allowed a reduction in the running time of the engine by about 38% of the total working time. However, only 35% to 41% of the Diesel-based mechanical's energy was consumed by the mainline and haulback winches, while the remaining energy was consumed by the other winches of the cable line system (skyline, strawline winches and carriage recharging or breaking during outhaul) or dissipated by the system (e.g., by the haulback blocks). By considering all the work cycles, the highest Net EC occurred during the inhaul-unload work element with a maximum of 1.15 kWh, consuming 70% of total Net EC to complete a work cycle. In contrast, lower energy consumption was recorded for lateral skid and outhaul, recording a maximum of 23% and 32% of the total Net EC, respectively. The estimated recovered energy, on average between the four cable lines, was 2.56 kWh. Therefore, the reduced fuel need was assessed to be approximately 730 l of fuel in the 212.5 PMH_{15} of observation, for a total emissions reduction of 1907 kg CO_2 eq, 2.08 kg CO_2 eq for each work cycle.

Keywords: timber harvesting; transportation; carbon emission; steep terrain, forest operation

5.2 Introduction

The impact of fossil fuel-based energy is considered one of the main environmental threats facing the planet. Alternative fuels and different propulsion systems have been proposed to perform low emission or zero-emission vehicles (Daziano and Chiew, 2012). The use of full electric and hybrid vehicles, especially in the transport sector, has increased substantially in the last few years compared to internal combustion engine vehicles (Correa et al., 2019). As a result, different studies have been conducted to analyse the energy efficiency of these power systems applied to light and heavy-duty vehicles, such as road vehicles, city mobility vehicles, and non-road vehicles (Chan, 2002; Chasse and Sciarretta, 2011; Ehrenberger et al., 2020; Kärhä et al., 2018a; Kulor et al., 2021; Weiss et al., 2020; Zhou et al., 2021). Even though hybrid and full electric propulsion systems are widely studied for road vehicles and city mobility applications (European Commission, 2018), there is currently a considerable knowledge gap in regards to hybrid and full electric propulsion systems in heavy-duty vehicles (Vijayagopal and Rousseau, 2020). Although heavy-duty vehicles are not as widespread as road vehicles, they are responsible for over 5% of greenhouse gas emissions (GHG) of the EU-27 countries (ACEA, 2020). For these reasons, new regulations (e.g. EU Regulation 2016/1628) have been progressively introduced in Non-Road Mobile Machineries (ARCADIS et al., 2010).

To achieve the ambitious climate change targets, low emission and zero-emission engines have also been introduced in the agricultural and forestry sectors. The first result of the electric-hybrid application in the agricultural sector shows that the electric traction drive applied to a farm tractor can reduce energy consumption by 12% (Deryabin and Zhuravleva, 2020). In comparison, hybrid powertrains with smaller Diesel engines can reduce energy consumption by up to 16% compared to bigger ones, ensuring more efficient energy usage in hybrid electric tractors (Mocera and Somà, 2020).

The first application of hybridisation or electrification in heavy-duty machines in the forest sector have involved the CFJ20H 320 V harvester (Rong-Feng et al., 2017), EcoTrac 120V skidder (Karlušíc et al., 2020) and Kesla's C 860 H hybrid wood chipper (Prinz et al., 2018a). As reported in Rong-Feng et al. (2017), the hybridisation of the CFJ20H 320 V harvester met the design requirement in regards to grade, maximum speed, acceleration time, and fuel consumption. The backward powertrain model of a skidder, optimised through a cascade optimisation approach using specific algorithms to minimise fuel consumption and satisfying transmission components constraints (Karlušíc et al., 2020), shows an efficiency improvement of over 15%. The algorithm optimisation can lead to a fuel reduction of 0.4 l per driving cycle and, consequently, reduce approximately 6 516.00 € in fuel cost and 15 900 kg in CO_2 emissions over the li-ion cells battery lifetime (15 000 cycles). Kesla's C 860 H hybrid wood chipper resulted in higher efficiency than conventional wood chippers (Kesla C 1060 A and Kesla C 1060 T). A study by Prinz et al. (2018) demonstrated lower fuel consumption of 0.2 l and 0.4 l per o.d.t. (oven dried ton) of pulpwood for high power truck-mounted and medium power tractor-mounted wood chippers, respectively.

In 2015, Koller Forsttechnik presented the first prototype of a hybrid cable yarder (Koller K507e-H) (Visser, 2015). This Diesel-electric configuration of the Koller K507e-H cable yarder expected to reduce fuel consumption by up to 3-5 l/h thanks to an energy recovery system. Furthermore, noise exposure for workers is also expected to be reduced due to a decrease in time with the engine on. However, to date, no study has tested the hybrid cable yarders, in order to assess the energy efficiency in terms of energy and fuel consumption.

In cable yarding operations, an active slack-pulling electric power carriage with an energy-recovery system (SPC), powered by the mainline when it is pulled or when the load is lowered, proves to be useful machines in order to reduce the fuel consumption during timber extraction. As reported by Varch et al. (2020), the 13 electric carriages currently available on the market recover energy during different working elements: when the carriage runs from the landing to the hooking area (outhaul), when the load is pulled up to the carriage (lateral skid), or when the carriage stops at the landing area, and the load is lowered (unload).

The hybrid cable yarders and SPC could present an opportunity to increase the energy efficiency of forestry operations, which would lead to lower emissions and economic savings due to reduced fuel consumption. However, there is still a considerable knowledge gap in regard to energy efficiency and fuel consumption of these electric-hybrid technologies. Therefore, this study aims to partially addressing this knowledge gap assessing energy efficiency and fuel consumption of a hybrid cable yarder equipped with an EC. The specific objectives of the present study are: (i) to quantify the energy consumption (kWh) of cable yarding operations using a hybrid cable yarder and an SPC; (ii) to assess the total energy efficiency of the yarding system estimated by the percentage ratio between the energy consumed during working activity (kWh) and the energy generated by the Diesel engine (kWh); (iii) to estimate the CO_2 equivalents emissions (CO_2 eq) saved due to the energy recovery system.

5.3 Methods

5.3.1 Machine description

The machine monitored in the study is a Koller K507e-H hybrid yarder. This hybrid yarder is a mobile tower yarder for standing skyline logging operations mounted on a 2-axle trailer (Table 5.1).

***Table 5.1** - Characteristics of hybrid cable yarding system*

Characteristics	Unit	Value / Description
Engine	-	Deutz F3L2011, 3 cylinders, Stage IIIA[1]
Power	kW	35.8
Vehicle base	-	2-axle trailer
Tower height	m	11
Skyline		6/26 IWRC
No. Diam.	mm	18
Lenght	m	1000
Tensile force[2]	kN	89
Mainline		6/26 IWRC
No. Diam.	mm	10
Lenght	m	2000
Tensile force[3]	kN	25
Haulback line		6/26 IWRC
No. Diam.	mm	10
Lenght	m	2000
Tensile force[3]	kN	25
Strawline		AmSteel-Blue
No. Diam.	mm	6
Lenght	m	2000
Tensile force[3]	kN	11
Carriage		Koller Ecko Flex
Mass	kg	600
Payload	kN	20

No. Diam.: nominal diameter
[1]Homologation declared by the cable yarder manufacturer (Koller GmbH, 2020)
[2]Tensioning drum
[3]Constant over the entire drum diameter

The machine is equipped with an F3L2011 Deutz 3-cylinder Diesel engine (35,8 kW), with specific fuel consumption at 1800 rpm and 75% of the load of 225 g/kWh (Deutz AG, 2011). The Diesel engine drives the electric generator, while each one of the four main drums (skyline, mainline, haulback line, and strawline) is driven by an electric motor and equipped with spring-loaded, hydraulically-opening, multi-disc brakes. When the energy balance is positive (i.e., the energy generated by the drums is greater than the energy consumed), the surplus of energy is converted and stored in the 700 V supercapacitor through an electric generator. The "start and stop" parameters of the Diesel engine can be modified from the machine settings. When the electrical potential of the battery pack falls below the set threshold (conventionally 15-20%), the Diesel engine automatically switches on to charge the battery pack by converting mechanical energy into electrical energy via the electric generator (Koller Forsttechnik, 2019).

The hybrid cable yarder is equipped with a Koller Ecko Flex carriage, an automatic clamped carriage with active slack-pulling system. The slack-pulling system is controlled by an electric motor which is powered by the 300 V electric capacitor. The electric motor consists of two batteries of 12 V and 7.2 Ah (86.4 Wh). The mainline runs inside the carriage through a pulley system. When the mainline is pulled by the electric winch of the cable yarder or when the load is lowered, the pulley system allows the battery pack to be recharged. This condition occurs during the lateral skidding and the lifting of the loads to the carriage.

The Koller K507e-H hybrid is equipped with a control panel consisting of the Koller Multi Matik screen and two joysticks. Through the Koller Multi Matik screen, it is possible to adjust settings and to monitor operating parameters in real-time (e.g., the maximum tensile force of the skyline, mainline, haulback line, strawline, and guyline; modify or deactivate the mainline drum and haulback drums; monitor the charging voltage of the supercapacitor). In addition, due to the Koller Ecko Flex carriage compatibility with the Koller Multi Matik, it is also possible to monitor the charging voltage of the carriage electric capacitor.

5.3.2 Study area and cable line configurations

The study area was located in the Natural Park of Paneveggio Pale di San Martino (Trentino Province, coordinates in WGS84: 46°17'53.9592", 11°45'23.9940"), in the North-Eastern Italian Alps, at 1555-1680 m a.s.l. (Figure 5.1). The ground was characterised by an average slope of 20 %, uneven rough terrain. The area was covered by a mixed even-aged stand composed by Norway spruce (*Picea abies Karst.*), silver fir (*Abies alba Mill.*), and European larch (*Larix decidua Mill.*). The stand area was affected by a large scale windthrow caused by the Vaia storm at the end of October 2018 (Chirici et al., 2019; Motta et al., 2018).

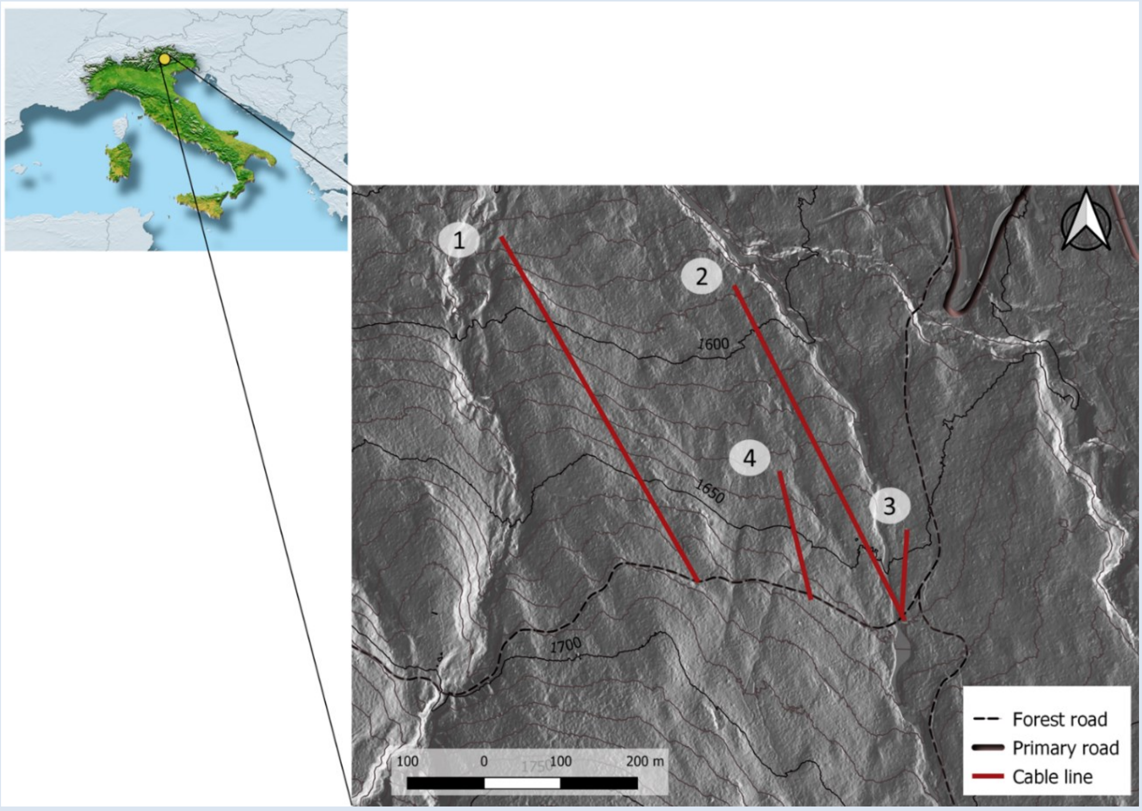

Figure 5.1 *- Location of the logging area and cable lines*

The observation interested four different cable lines. Three of the four lines were in multi-span configuration and one in single-span configuration (Table 5.2). The longest cable line was the cable line 1 with an horizontal length of 502 m, while the shortest was cable line 3 with 109 m of horizontal lenght. The four cable lines were in three cables uphill yarding configurations (skyline, mainline and haulback line). The logs were extracted at the roadside landing where an excavator, equipped with a log grapple, piled up the log along the forest road.

Table 5.2 *– Cable line configurations*

Cable line	HL (m)	VL (m)	N° span	Slope (%)
1	502	107	3	21.3
2	480	70	3	14.5
3	109	20	1	12.0
4	164	31	2	18.6

HL: horizontal length, measured from the tower yarder to the anchor; VL: vertical length, measured as altitudinal difference between the starting point (tower yarder) and the endpoint of the corridor (anchor); Slope (%): average slope of the cable line, measured from the cable yarder to the anchor

5.3.3 Data collection

The monitoring period was between July 2020 and September 2020. The position (coordinates) of the tower yarder and tail anchors of each cable line was taken with a Garmin 64s GNSS. QGIS® software was used to estimate horizontal length and vertical length of each cable line computed as the horizontal and vertical distance from the cable line's tower yarder to the anchor from the digital elevation model (DTM) with a resolution of 1 m. Data were collected through the integration of long-term monitoring (LTM) using Can-BUS data, self-monitoring data, and direct field monitoring (FM). Can-BUS data were downloaded directly from the cable yarder at the end of the monitored period. Can-BUS data were recorded at 4 Hz and saved in 8 bits. The following pieces of information were collected from the Can-BUS data:

- energy-storage (V);
- electric power of the winches (kW);
- speed of wire (m/s);
- distance of carriage off the tower (m);
- power electric generator (kW);
- tensile force of mainline (N);
- tensile force of haulback (N).

For the self-monitoring data collection, the operator was instructed to record the daily data about fuel consumption (recorded measuring the volumes of fuel tank refills), number of work cycles and type of activity (cable yarding extraction or cable yarding installation) for each cable line.

Finally, the FM aimed at evaluating and control the LTM (e.g., check the correctness of the automatic time and motion study) data and covered a total of four different working days (22.5

PMH_{15}). Cable line 1 was monitored for 11.1 PMH_{15} and 46 work cycles, while cable line 2 was monitored for 11.5 PMH_{15} and 50 work cycles.

In order to evaluate the input of time in the production process of each work cycle, as reported by Björheden (1991), a time study of the cable yarding operations at cycle level was carried out using a time study board. In addition, the fuel consumption of each cycle, as displayed on the Koller Multi Matik screen, was noted, and the timber volume extracted (m^3 o.b.) by each cycle was measured scaling each log, using a calliper and a measuring tape.

5.3.4 Data analysis

About 900 MB of Can-BUS data and more than 4 million row data were downloaded from the cable yarder. The Can-BUS data were converted from 8 bits information (0 to 255) to decimal encoding and subsequently resampled at 1 Hz data using the R software (R Core Team, 2021). Days spent for cable line set-up were excluded from the analysis using self-monitoring data collected by the operator. Automatic time study data was retrieved from the Can-BUS data. Each yarding cycle and related work elements were obtained from the decoded Can-BUS data using the winches power and the distance of the carriage from the tower yarder. (Table 5.3, Figure 5.2).

Table 5.3 *– Description of the work elements*

Work element	Description	Carriage motion
Outhaul	Begins when the haulback line is rolled up and mainline is rolled out while the carriage moves from the landing site to the hooking area, ends when the carriage stop at the hooking area	Yes
Lateral skid	Begins when the mainline is rolled up while haulback does not generate or consume energy (inactive), ends when the carriage moves from the hooking area back to the landing site	No
Inhaul-unload	Begins when the mainline is rolled up and haulback line is rolled out while the carriage moves from the hooking area to the landing site, ends when the carriage moves from the landing site to the hooking area	Yes

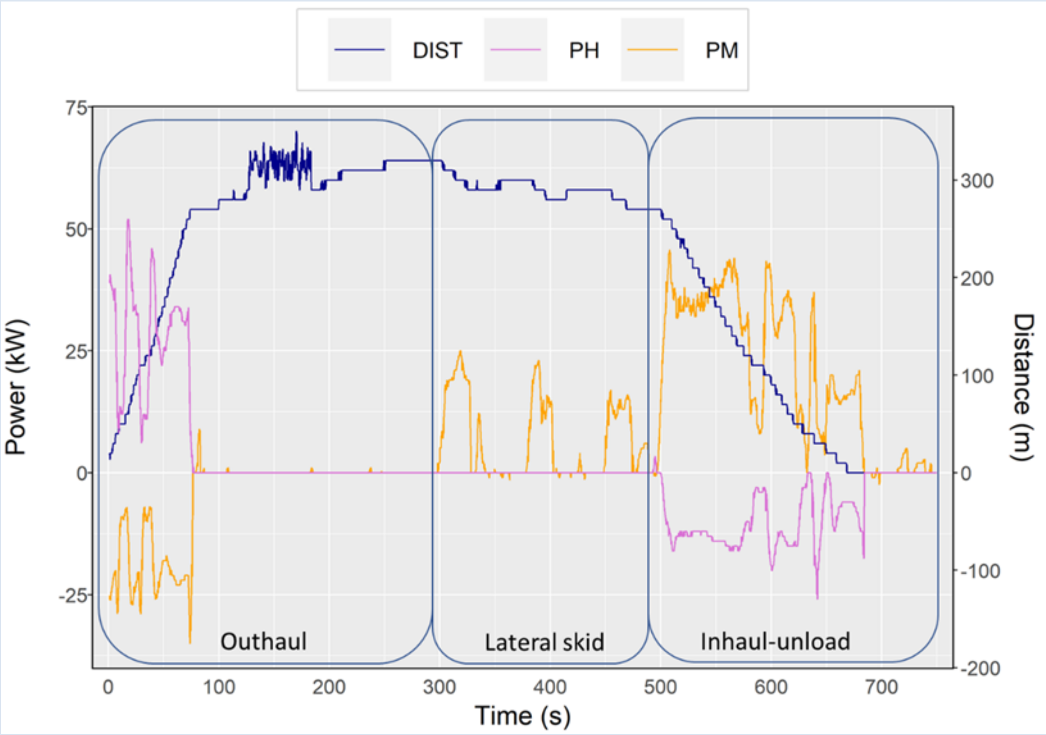

Figure 5.2 *- Automatic time and motion study retrieved from Can-BUS data. DIST: Distance of the carriage off the tower (m); PH: Power generated or consumed by the haulback winch (kW); PM: Power generated or consumed by the mainline winch (kW); positive values of power (kW) refer to an energy consumption while negative values refer to energy recovery*

Non-productive time was determined when the electric power of the winches, speed of the wire rope, the tensile force of mainline and tensile force of haulback line were equal to zero. Non-productive times longer than 15 min suggested that the machine was completely shut down and, therefore, were excluded in the analysis leading to the adoption of the Productive Machine Hour including delays not exceeding 15 minutes (PMH_{15}). Finally, the actual yarding operations interested 915 complete work cycles over 30 working days, for a total of 212.5 PMH_{15}.

The parameter used for evaluating the yarding system's total energy efficiency was the net energy consumption of the winches (kWh), and the energy generated by the Diesel engine expressed as electric energy (kWh). The net power supplied to drive the winches - Net PC - was calculated for each work element and cycle using eq 1:

$$Net\ PC\ (kW) = PC\ (kW) - PG(kW) \qquad \text{eq. 1}$$

where PC was power consumed, calculated from the sum of energy consumed from the mainline winch and haulback winch, expressed in kW; PG was the power generated, calculated from the sum of energy generated from the mainline winch and haulback winch, expressed in kW. To calculate net energy consumption during working activity, the averaged Net PC (kW) for each work element was multiplied by the time required to complete the work element - WE_{PMH15} - (eq. 2):

$$Net\ EC\ (kWh) = Net\ PC\ (kW) * WE_{PMH15}(h) \qquad \text{eq. 2}$$

The energy produced during a work cycle by the electric generator powered by the Diesel engine – EP - expressed in kWh, was estimated multiplying the mean power generated by the electric generator while the Diesel engine was running – PGE - expressed in kW, by the time the engine was on – TO - expressed in hours and represents part of PMH15 (eq. 3):

$$EP\ (kWh) = PGE\ (kW) * TO\ (h) \qquad \text{eq. 3}$$

Typically, the energy stored in the supercapacitor during a single cycle can be used in subsequent cycles. Due to the dependence on the powertrain between work cycles, total energy efficiency -TEF- was evaluated in term of the percentage ratio between the net energy consumed during working activity with cable line as a unit of observation. The TEF was obtained by the sum of Net EC of the work elements and the energy produced during each work cycle (EP) (eq. 4):

$$TEF\ (\%) = \frac{\sum Net\ EC\ (kWh)}{EP\ (kWh)} * 100 \qquad \text{eq. 4}$$

Automatic time study and energy information at cycle levels collected through LTM and data obtained through FM were synchronised and combined with extracted timber volume and number of logs per cycle. The correctness and completeness of the data were checked. The fuel consumption model was tested through linear regression analysis using EP (kWh) as an explanatory variable for the fuel consumed for each cycle (l) collected during FM. The hypothesis of the normal distribution of the residuals was checked using the Shapiro-Wilk normality test (p-value > 0.05).In the case of statistical significance, the regression coefficients of the regression were used to extend the fuel consumption estimation to the LTM data.

The emissions saved were estimated by applying TEF parameter for each line to the average energy saved (kWh) to obtain EP (kWh) of the engine. As proposed by De la Fuente et al. (2017), CO_2 emissions were estimated using an emission factor of 2.61 kg CO_2 eq per litre of Diesel fuel consumed.

5.3.5 Energy consumption model

Different independent variables were checked as explanatory variables for the Net EC evaluated at each work element. The independent variables were: yarding distance, estimated by the maximum distance travelled by the carriage – YD (m), maximum speed – MS (m/s), mean tensile force of mainline - MTFM (kN), mean tensile force of haulback line - MTFH (kN).

Due to the diversity of the Net EC per work element within cable lines, the response variables were considered as repeated measures within each individual cable line, as reported by different studies (e.g., Hiesl and Benjamin, 2013; Bates et al., 2015; Mologni et al., 2019; Cadei et al., 2020). The different cable lines were assumed to be random factors, and a random intercept for the different cable lines was introduced in the regression analysis, leading to the adoption of linear mixed-effect models. The likelihood ratio test was used to evaluate the significance of the individual variables, with the significance level of the statistical analysis set to 0.05. A Linear mixed-effect model was fitted with the lme4 package available for R (Bates et al., 2015b). The normal distribution of the residuals was checked using residual plot distributions. In the case of non-normal distribution of the residual, logarithmic, quadratic, and square root transformations were tested on both response variables and continuous explanatory variables. The goodness of fit of linear mixed effect models was tested through the coefficient of determination (R^2_{LR}) proposed by Magee (1990) (eq. 5) and based on likelihood ratio joint significance:

$$R_{LR}^2 = 1 - \exp\left(\frac{-2}{n} * (l_M - l_0)\right) \qquad \text{eq. 5}$$

where "l_M" and "l_0" are the log-likelihoods of the model of interest and of the intercept-only model, respectively, and "n" is the number of observations.

5.4 Results

Monitored work cycles and days varied between the cable lines (Table 5.4).

Table 5.4 *– Description of LTM*

Cable line	**Tot time**	**Cycle**	**Net $EC_{outhaul}$**		**Net $EC_{lateral\text{-}skid}$**		**Net $EC_{inhaul\text{-}unload}$**		**TEF**	**Engine on**	**Yarding distance**	
	PMH_{15}	n°	kWh		kWh		kWh		%	%	m	
			Mean	SD	Mean	SD	Mean	SD			Mean	SD
1	114.94	422	0.273	0.12	0.231	0.16	1.150	0.36	40.7%	73.6%	380.3	93.6
2	81.99	338	0.336	0.27	0.287	0.26	0.837	0.59	35.6%	68.7%	281.0	129.7
3	3.14	42	0.045	0.03	0.086	0.03	0.237	0.06	35.3%	51.8%	85.5	15.4
4	12.44	113	0.035	0.04	0.132	0.08	0.245	0.10	41.4%	38.2%	80.4	39.5

Engine on: sum of the time engine on divided by the total working time (PMH_{15})

The shortest single span cable line (1) recorded the lowest Net EC during the lateral skid and inhaul-unload work element, 0.086 and 0.237 kWh per work cycle, respectively. On the contrary, cable lines 1 and 2 with higher yarding distances, 380 and 281 m respectively, recorded a higher value of Net EC for the whole work element than cable lines 3 and 4. Also, in cable lines 1 and 2, the engine was running for more than two-thirds of the working time (PMH_{15}), producing 35 to 40% of the Net EC. As expected, Net EC for all work elements increased as the yarding distance increased (Figure 5.3).

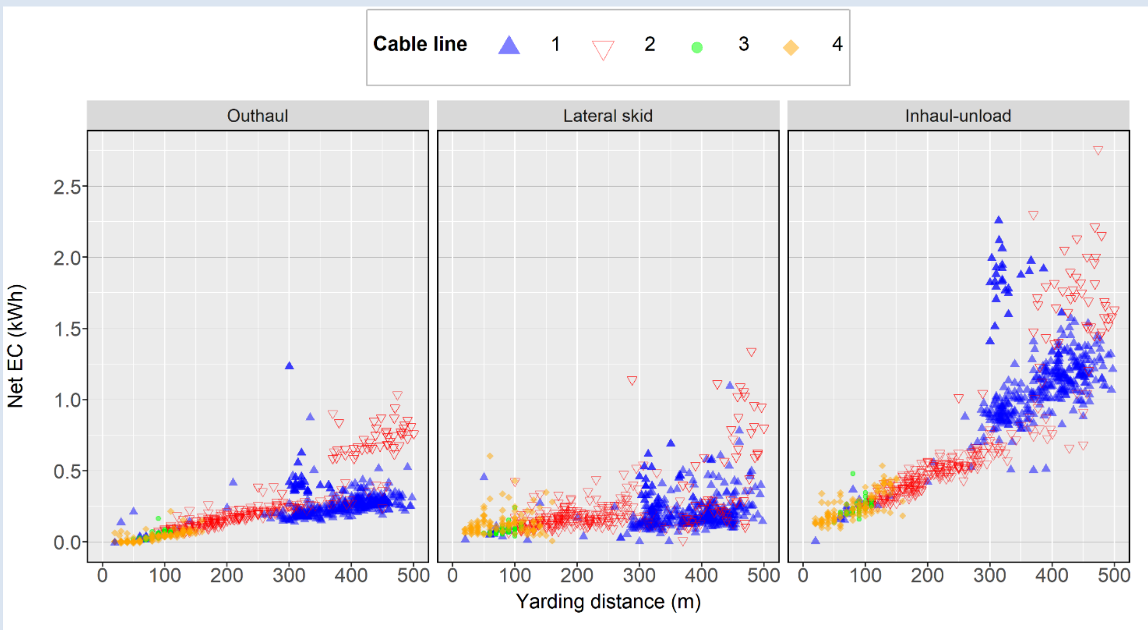

Figure 5.3 *- Net EC (kWh) for outhaul, lateral skid and inhaul-unload working element in respect of the yarding distance (m)*

The percentage of the time with Diesel engine on varied considerably between the cable lines, from a minimum of 38% for cable line 4 to 73% for cable line 1. Also TEF varied from a minimum of 35% to a maximum of 41% for cable lines 3 and 4, respectively. The lowest TEF was related to cable line 3, characterized by the lowest line slope (12%).

Because of the uphill yarding, the inhaul-unload work element was the most energy-consuming. Net EC during lateral skid exceeded Net EC during outhaul only in cable lines 3 and 4. This suggests that the reduced yarding distance of lines 3 and 4 led to a reduction in the energy consumed during outhaul and inhaul-unload.

Subsequently, Can-BUS data were evaluated and controlled according to FM data (Table 5.5). During the FM, a total of 100.6 m^3 were yarded and measured, 57.1 m^3 in cable line 1 and 43.4 m^3 in cable line 2. Descriptive statistics related to FM are reported in Table 5.

The emissions related to the FM's yarding activity were 84.04 kg CO_2 eq and 93.77 kg CO_2 eq equal to 1.47 kg CO2 eq/m^3 and 2.16 kg CO2 eq/m^3 for cable line 1 and cable line 2, respectively.

Table 5.5 *- Descriptive statistics of FM*

Cable line	Tot time	Cycle	Yarding distance		Lateral skid distance		Load		Productivity		Fuel consumption	
	PMH_{15}	n°	m		m		m^3/cycle		m^3/PMH_{15}		l/m^3	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	10.99	46	309	51	15.5	1.2	1.20	0.30	5.70	2.40	0.56	0.21
2	11.44	50	447	52	17.5	2.5	1.00	0.20	5.00	1.70	0.80	0.18

Electric energy produced by the Diesel engine (kWh) significantly affected fuel consumption (l). Therefore, the predicted fuel consumption (l) showed a correlation to the electric EP (R^2=0.52, p value <0.001) (Table 5.6). Using the relationship between EP and fuel consumption, it was also possible to estimate fuel consumption for the LTM activity. During the LTM, the hybrid technology allowed for the recovery of an average of 2.56 kWh per cable line, ranging from a minimum of 0.91 for cable line 3 to a maximum of 5.01 kWh for cable line 4. An estimated total of 730.7 l of fuel was saved. This fuel saved can be considered as a reduction of emission impact equal to 1907.1 kg CO_2 eq and 2.08 kg CO_2 eq for each work cycle.

Table 5.6 *- Linear regression model to predict fuel consumption (l) from the electric energy (EP) produced by the Diesel engine (kWh)*

Coefficient	Estimate	SE	*t* value	*p* value	R^2
Intercept	0.236	0.642	3.667	<0.001	0.52
EP (kWh)	0.089	0.104	6.323	<0.001	

The estimated productivity, fuel consumption and emissions are shown in Table 5.7. The lower productivity was estimated for the longest cable lines (1-2); therefore the cable line 1 and 2 consumed more fuel per unit of timber extracted (0.54 and 0.55 l/m^3, respectively) compared to the cable line 3 and 4 (0.28 and 0.27 l/m^3, respectively). Consequently, the estimated CO_2 eq emissions per unit of timber extracted were highest for the longest cable lines than the shortest ones (1.41, 1.44, 0.73 and 0.70 kg CO_2 eq/m^3 for cable lines 1,2,3 and 4, respectively).

Table 5.7 *- Estimated productivity, fuel consumption and fuel emission based on FM data*

Cable line	**Extracted volume**	**Productivity**	**Fuel consumption**	**CO_2 eq emission**
	m^3	m^3/PMH_{15}	l/m^3	kg CO_2 eq/m^3
1	464	4.04	0.54	1.41
2	372	4.53	0.55	1.44
3	46	14.71	0.28	0.73
4	124	9.99	0.27	0.70

5.4.1 Energy consumption equations

As shown in Figure 5.3, the yarding distance – YD (m) - suggest a significative and positive correlation on Net EC for all the elements of the work cycle. The three equations (A, B and C) carried out for each work elements, shown in Table 8 and Table 9, explain the energy consumption equation.

Equation A is related to the Net EC during outhaul and explains 53% of the variability, where each metre of increase in YD leads to an increase of Net EC of 1.3 Wh. Equation B explains 30% of the variability. The mean tensile force of the mainline during lateral skid - $MTFM_l$ (kN) - had a negative effect on Net EC, meaning that increasing $MTFM_l$ during lateral skid can lead to a reduction of the energy consumed. On average, the $MTFM_l$ was 10.3, 10.7,11.7 and 11.2 kN for cable lines 1, 2, 3 and 4, respectively. Equation C explains over 78% of the variability. As expected, the mean tensile force of the haulback line during the inhaul-unload work element – $MTFH_{in}$ (kN) – had a negative influence on the Net EC of the same work element.

Table 5.8 *- Explanatory variables of fixed effect in Net energy consumption, Net EC (kWh), during the different work elements*

Equation	Response variable	Coefficient	Estim.	SE	*t* value	*p*-value
A	Net $EC_{outhaul}$ (kWh)	YD (m)	0.0013	0.037	−2.47	<0.001
B	Sqrt(Net $EC_{lateral\ skid}$) (kWh)	YD (m)	0.0008	0.00005	18.06	<0.001
		$MTFM_l$ (kN)	-0.0088	0.00130	-6.54	<0.001
C	Ln(Net $EC_{Cinhaul\ unload}$) (kWh)	$MTFH_{in}$ (kN)	-0.0182	0.006	-2.928	0.002
		$SDTFM_{in}$ (kN)	0.1048	0.008	12.53	<0.001
		Sqrt(YD) (kN)	0.1455	0.002	60.67	<0.001

Ln: logarithmic transformation; YD: yarding distance (m); $MTFM_l$: mean tensile force of mainline during lateral skid (kN); $MTFM_{in}$: mean tensile force of mainline during inhaul unload element (kN); Sqrt: square root transformation

Table 5.9 *- Random intercepts and goodness of fit of the linear mixed-effect models*

Equation	N	Variance	SD	L_M	L_0	R^2_{LR}
A	915	0.01774	0.133	594.4	253.2	0.527
B	915	0.00660	0.081	536.4	371.7	0.302
C	915	0.45420	0.674	-34.2	-733.3	0.783

N: number of observations; L_M: log likelihoods of the model; L_0: log likelihoods of the intercept; R^2_{LR}: coefficient of determination proposed by Magee (Magee, 1990)

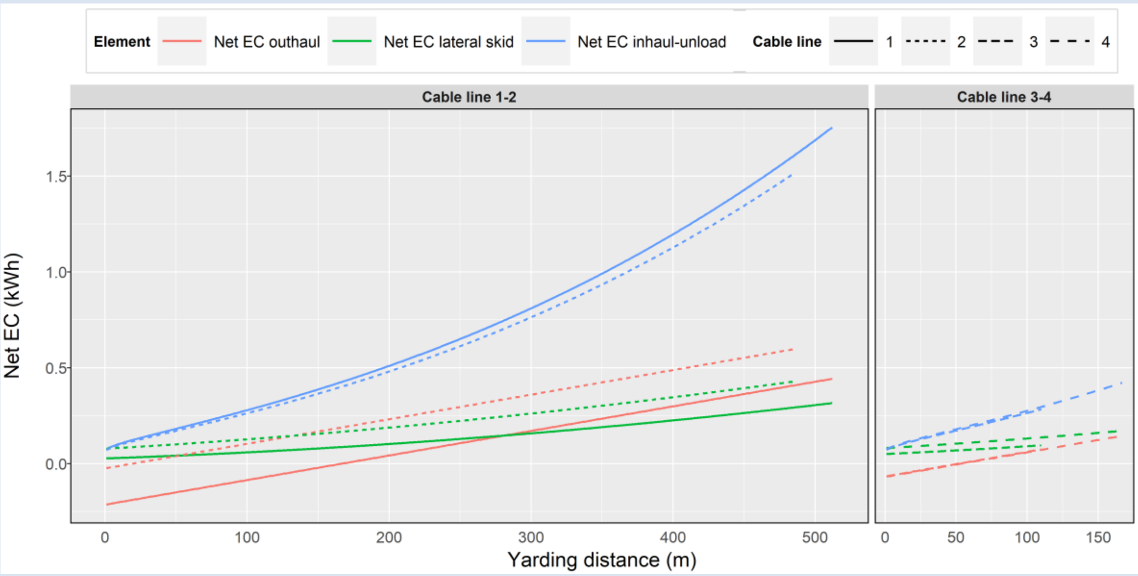

Figure 5.4 *- Net EC energy consumption (kWh) plotted over yarding distance in the four monitored cable lines*

In conclusion, the YD had a significant effect and positive correlation on Net EC for all the work elements. The influence of YD on energy consumption changed according to the work element (Figure 4). Although inhaul-unload is the most energy-consuming, outhaul allows for an increase in energy recovery. In fact, for short YD (< 150 m) in uphill cable yarding configurations, the Net EC shows negative values and therefore represents an energy-producing element of the work cycle.

5.5 Discussion

Hybrid powertrains are expected to reduce fuel consumption thanks to an energy recovery system. Excluding set-up/installation of the cable lines, the Net EC of the system is based on the use of mainline and haulback winches alone. However, it can also be considered that a certain amount of energy may have been consumed by the carriage (energy recuperation system and the breaking of the carriage during the outhaul) or by the skyline winch during the skyline tensioning.

The monitored rigging configurations were the most energy disadvantageous due to the low line slope (limited to a maximum of 21%) and the uphill yarding. Fuel consumption is highly dependent on the slope of the line and the yarding direction, with higher fuel consumption recorded in uphill extraction than in flat conditions (Oyier and Visser, 2016). Consequently, due to the high fuel consumption for uphill yarding, it is expected that the related energy consumption is also higher. In general, YD significantly affects the Net EC of each work element, causing an increase in Net EC. Similarly, other authors reported the positive effect of yarding distance on time consumption (Lee et al., 2018; Lindroos and Cavalli, 2016; Proto et al., 2016b; Spinelli et al., 2010; Stoilov et al., 2021). Hybrid powertrains of the cable yarder in an uphill configuration recover most of the energy when the carriage moves from the landing to the hooking area, using the excess potential energy generated by the mainline drum when the mainline is rolled out. A small amount of energy can also be recovered when the carriage moves from the hooking area to the landing, using the haulback drum's excess potential energy when the haulback line is rolled out. However, the energy consumed by the mainline drum when the carriage moves from the hooking area to the landing, carrying the loads against gravity, is much greater than that recovered by the haulback drum during the same work element. The higher the MTFHin, the lower the Net EC during the inhaul-unload, suggesting the conversion of the tensile force into energy stored in the supercapacitor. In contrast, the standard deviation of the tensile force of the mainline – SDTFMin (kN) – had a positive effect on the Net EC during the inhaul unload work element. This finding suggests that the rise and fall of tensile force during inhaul unload causes an increase in energy consumption. The change in tensile force may be due to the reduced tensioning of the skyline which caused an increase in the mainline tensile force while passing a support structure.

In terms of fuel consumption, Varch et al. (2020) demonstrated that the SPC uses less fuel than an engine-powered slack-pulling carriage over short yarding distances (25 and 100 m) and with average tree volumes lower than 0.7 m^3. Our results show that also in disadvantageous energy consumption conditions (low line slope and uphill yarding) with yarding distances lower than 150 m, the movement of the carriage from the landing to the hooking area can take place without consuming energy and, under certain circumstances, can even generate energy effectively exploiting the conversion of potential energy into electrical energy. Assuming an efficiency of conversion of mechanical energy into electrical energy, the relationship between fuel consumption (l) and electrical energy produced by the Diesel engine (kWh) is consistent with the average fuel consumption of 0.09 litres per unit of power (l/kWh) for cable yarding harvesting system reported in Oyier and Visser (2016). The fuel consumption of the hybrid cable yarder ranged from 0.5 to 0.8 l/m^3 for a yarding distance of 300 and 450 m and an average load of 1.2 and 1 $m^{3,}$ respectively (Table 4). Considering the total energy efficiency – TEF - and the relationship between EP and fuel consumption (Table 5), the predicted fuel consumption (Figure 5) was considerably lower compared to Diesel engine cable yarders which range from 2.35 to 3.98 l/m^3 as reported by Oyier and Visser (2016). Furthermore, Varch et al. (2020) reported the comparison between fuel consumption of Diesel engine and SPC in similar working conditions (uphill yarding) using a truck-mounted tower yarder.

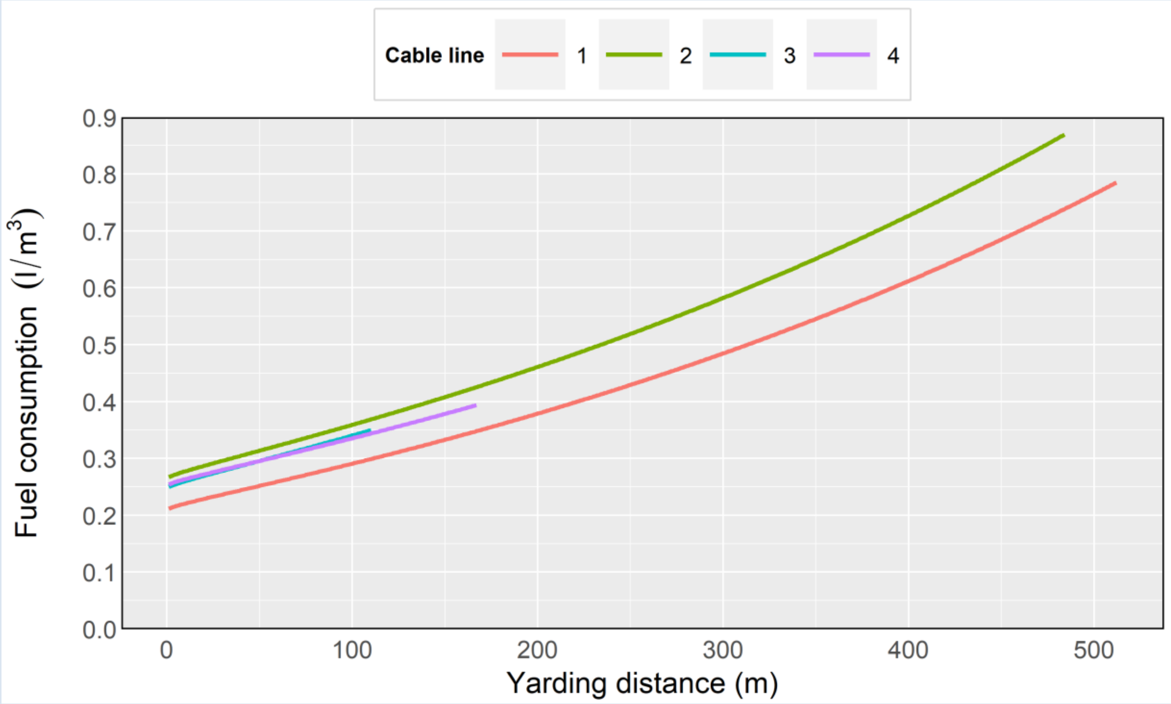

Figure 5.5 *- Predicted fuel consumption depending on the yarding distance*

Diesel engines, which powered both the carriage and the tower yarder, consumed 1.27 l/m^3, while the base machine used with an SPC consumed 0.88 l/m^3, with an average yarding distance of 62.2 and 54.7 m, respectively. In our study, at the same yarding distance, the predicted fuel consumption varied between 0.25 and 0.32 l/m^3, resulting in more than a quarter of the fuel consumption of a fully equipped Diesel engine tower yarder and carriage and about one third of the fuel consumption of the SPC and Diesel engine tower yarder. The gap in the literature on energy efficiency and fuel consumption on cable yarding did not allow for further comparison with other studies. The fuel consumption of a hybrid cable yarder and SPC per unit of timber extracted would therefore be lower than a traditional Diesel engine tower yarders and carriages. The fuel consumption is also lower than SPC with Diesel engine based machines. In contrast, the average productivity of the hybrid cable yarder of 5.35 m^3/PMH$_{15}$ was lower than the conventional Diesel engine cable yarder in similar conditions. Therefore, in terms of energy balance, the hybrid cable yarder and SPC are more advantageous than traditional Diesel based cable yarders. However, this study is focused on energy efficiency and not on productivity. Finally, further economic and cost analyses are needed to establish the economic benefit of these applications.

5.6 Conclusion

This study monitored cable yarding operations under real working conditions and demonstrates that hybrid cable yarders and SPC have the potential to reduce energy consumption and save fuel and emissions. Although this study provides information about energy efficiency and fuel consumption, the main limitation of the study is related to the cable line configuration. In fact, to better understand the efficiency of the energy recovery system of the hybrid cable yarders in the Alpine context, further studies are needed, including downhill and uphill extractions as well as two- and three-line cable yarding systems. The study also found that the Can BUS system allows to easily collect long-term information of the performance of the powertrains, as well as integrate and analyse long-term data correctly, particularly when combined with field observations.

Finally, given the reduced time during which the yarder engine was running, the study suggests that the noise exposure of forest operators could be lowered by using hybrid solutions compared to conventional machines. In addition, a powerful Diesel engine with high performance can reduce the charging time of the supercapacitor, further reducing the time engine on and optimising the fuel consumption. However, further studies need to carry out to determine the effect of hybrid powertrains on noise pollution. The smaller amounts of hydraulic and engine lubricants for the operation of the hybrid propulsion systems should also be taken into consideration because it may lead to lower impact timber harvesting and ensure safety of forest operators.

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6 Paper V - Evaluation of wood chipping efficiency through long-term monitoring

Alberto Cadei [1,*], Luca Marchi [1], Omar Mologni [2], Raffaele Cavalli [1] and Stefano Grigolato [1]

[1] Department of Land, Environment, Agriculture and Forestry, Università degli Studi di Padova, Viale dell'Università 16, 35020 Legnaro, PD, Italy; luca.marchi@unipd.it (L.M.); raffaele.cavalli@unipd.it (R.C.); stefano.grigolato@unipd.it (S.G.)
[2] Department of Forest Resources Management, Faculty of Forestry, The University of British Columbia, MainMall 2424, Vancouver, BC V6T 1Z4, Canada; omar.mologni@ubc.ca
* Correspondence: alberto.cadei@phd.unipd.it
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6.1 Abstract

A high volume of wood forest biomass is be available at the roadside when whole tree (WT) harvesting systems are applied. Besides, salvage logging operations are favourable conditions to accumulate a large amount of low-quality biomass due to the recovery of damaged trees. In mountain regions, such as the Alps, the forest's accessibility can be a significant constraint for the eco-efficiency of chipping operations. The present study aims at evaluating the efficiency of wood-chipping operations in mountain areas based on long-term monitoring. One chipper-truck was monitored over 1200 working hours using telemetry. Different efficiency parameters were collected: machine position, collected using Global Navigation Satellite System (GNSS) receiver, and engine parameters, collected using the CAN Bus system based on J 1939. Efficiency parameters were used to compare different in-wood or landing configurations. The results show the influence of the different location of the chipping sites according to the road network. Chipping operations in space-constrained sites cause an increase in delay time and CO_2 emissions.

Keywords: telemetry; efficiency; biomass; residues; emissions

6.2 Introduction

Due to climate change, the production of energy from renewable sources has increased in recent years (Bais et al., 2015). Because of the climate neutrality 2050 EU goal (European Commission, 2019), the European Commission is planning to reduce EU greenhouse gas (GHG) emission by at least 55% by 2030. In these situations, the energy used for producing energy from renewable sources needs to be optimised. Products made by biomass are typically considered low impact in terms of GHG emission compared to the equivalent product made from non-renewable sources (Petersen and Solberg, 2005).

The primary products from forestry and logging are industrial roundwood and fuelwood. In Italy, about four-fifths of the roundwood production was provided as fuelwood (Eurostat, 2020). Typically, after timber harvesting, a large quantity of low-quality biomass (LQB) such as non-commercial timber and logging residues are left on site. In recent years, the demand for LQB as feedstock for energy production has increased. Therefore, resource efficiency and GHG emissions from the forestry sector can be optimised by encouraging cascading biomass use (Keegan et al., 2013). In fact, after the merchantable timber harvester, LQB can be collected and chipped at roadside landings or terminals (Vance et al., 2018). However, in order to increase the efficiency in the recovery of LQB, all the processes involved in the biomass supply chain need to be considered (Asikainen et al., 2014).

Typically, whole-tree (WT) harvesting systems provide a higher volume of logging residues compared to cut-to-length (CTL) harvesting systems, where branches and unmerchantable top sections of trees are left in the cutting area (Hytönen and Moilanen, 2014). Furthermore, harvesting treatment affects the quantity of wood chips yielded: clear cuts in low-quality stands can generate a large quantity of biomass as well as salvage logging operations (Spinelli et al., 2020). Contrarily,, whole tree chipping in early thinning operations generate a lower quantity of fuelwood (Spinelli et al., 2016). Consequently, accumulated fuelwood can be chipped at the roadside landing or transported to terminals (Spinelli et al., 2007). Chipping at the roadside is less cost-effective than chipping at the terminals (De la Fuente et al., 2017); besides, in mountain regions, such as the Alps, forest accessibility can be a significant constraint for the eco-efficiency of chipping operations. When trucks and trailers or semitrailers are unable to reach working sites, chips can be shuttled outside forests with a truck or tractor with trailer units (Mihelič et al., 2018). Furthermore, when the yarding contractor does not coincide with the chipping contractor, some problems may arise (Mihelič et al., 2018). Good cooperation between yarding contractors and chipping contractors, in order to identify in advance the location to pile logging residues, can improve the efficiency of chipping (e.g., no stones or metal in the pile) and reduce the frequency of relocation (e.g., the number and size of logging residues piles)(Marchi et al., 2011). Using modern technology, it is possible to improve the economic, environmental and social sustainability of forest operations (Picchio et al., 2019).

Modern devices based on data transmission via GPRS-UMTS-HSDPA connections can be used to easily monitor and collect data of the entire wood chip production (Deboli et al., 2014), as it was also proposed by Holzleitner et al. (Holzleitner et al., 2013) using a fleet management system (FMS) to monitor chipping and transport activities.

This study, based on a semi-automated method, aims to evaluate the efficiency of wood chipping through long term monitoring based on FMS. More specific goals were to evaluate the efficiency and CO_2 equivalent emissions of wood chipping activities in mountain areas and to evaluate the effect of the accessibility of the work site on efficiency and CO_2 emissions.

6.3 Materials and Methods

6.3.1 Wood Chipper Details

The chipper-truck was based on the chipper unit, a Mus-Max Wood Terminator 10 XL, mounted on a three-axles truck, a MAN TGS-28.540. The 397 kW truck's engine powered the chipper unit. Chipping operations were carried out by the operators seated in the external cabin (Figure 6.1). Net productivity declared by the manufacturer of the chipper unit is 180 m^3/h. Details of the machine are reported in Table 6.1.

Figure 6.1 *- Mus-Max Wood Terminator 10 XL chipper-truck.*

Table 6.1 *- Detail of Mus-Max 10 Wood Terminator XL chipper-truck.*

Truck		
Manufacturer	-	MAN
Model	-	Man TGS 28.540
Engine type	-	Man 6 cylinders
Engine power	kW	397
Chipper unit		
Manufacturer	-	Mus-Max
Model	-	Wood-Terminator 10 XL
Feed opening	(w × h) mm	980 × 750
Tree diameter max	mm	750
Drum diameter	mm	900
Chopping knives	n°	12
Crane		
Model		Penz 14 L
Gross lifting torque	kNm	136
Maximum boom reach	m	10.1
Chipper-truck		
Weight	kg	27,000
Length	m	9
Width	m	2.5

6.3.2 Data Collection and Analysis

The chipper-truck was equipped with GSM/GNSS Teltonika FM3612 receiver in order to collect Can-BUS and machine position data. Data were recorded from January 2019 to May 2020 with an acquisition rate set at 1 Hz, as proposed by a similar study (Holzleitner et al., 2013). The web-server application for the acquisition of the data remotely was specifically developed for the study by Transpobank s.r.l. The data, downloaded from the server, include the following information: date-time stamp, position, altitude (m), travelling speed (km/h), engine temperature (°C), engine hours, engine speed (rpm), total fuel used (l) and odometer (m).

In order to detect working site and information related to the road characteristics, the position of the machine was linked with the regional and provincial road database of Lombardia, Veneto and Trentino-Alto Adige The accessibility of chipping sites was derived with respect to the public road and forest road classification: primary state and regional public roads (Easy condition), secondary public roads and main truck forest roads (Moderate condition) and secondary truck forest roads with few sites where the trucks can turn (Difficult condition).

A dedicated R code was developed for time and motion study analysis based on cycle level (Björheden et al., 1995) considering chipper position, chipper speed, engine speed and their combinations to detect the following work elements:

- Chipping (C): when travelling speed is under 1 km/h and engine speed is above 1500 rpm;
- Travelling (T): when travelling speed exceeds 1 km/h and engine speed is above 0 rpm;
- Operational delay (OD): when travelling speed is below 1 km/h and engine speed is below 1500 rpm;
- Non-operational delay and other delays (NOD): when engine (rpm) and travelling speed (km/h) are equal to 0.

The observation units were the working sites and the observations started with the first chipping element and finished with the end of the last one. The operator was instructed to record the chipping volume produced for in all the working sites separately.

6.3.3 Efficiency Calculation and Statistical Analysis

In order to evaluate the efficiency of the wood chipping operation, the following equation was used:

$$Efficiency(\%) = \left(\frac{\mathrm{C}}{\mathrm{C} + \mathrm{T} + \mathrm{OD} + \mathrm{NOD}}\right) * 100 \qquad (6)$$

The environmental impact of wood chipping was evaluated in terms of total CO_2 equivalent emission (kg CO_2 eq) in the different working sites taking in consideration the emission derived from all the work elements per working sites (T, C and OD). As proposed by De la Fuente et al. (De la

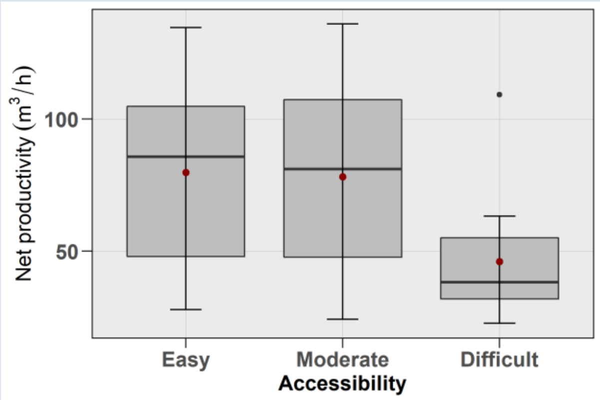
Fuente et al., 2017), fuel consumption (l) was converted into CO_2 eq using emission factors per litre of diesel fuel of 2.61 kg CO_2 eq.

Afterwards, all the data were analysed considering the working site as observational unit and classified per type of accessibility as defined before. The coefficient of determination (R^2) was used to evaluate the goodness of fit of the linear model. The significance level of the statistical analysis was set to 0.05. In case of non-normal distribution of the residual, square root and logarithmic transformations were tested on both dependent variables and independent variables.

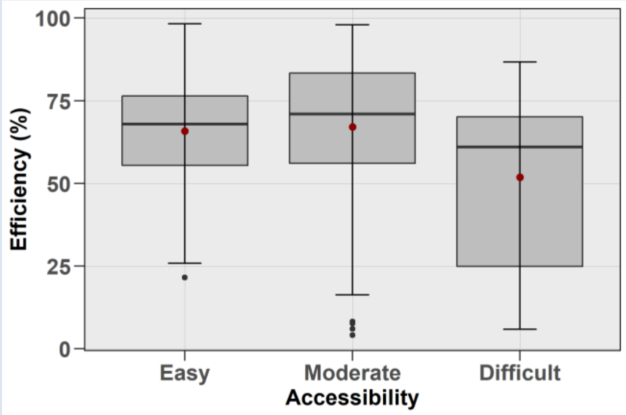
6.4 Results

The total working days were 168, and the chipping activities were divided into 288 different working sites. Working activities in the different working sites covered over 1200 h, 127 working sites (399 h) of these were registered as easy conditions, while 126 working sites (494 h) and 35 working sites (307 h) were recorded as moderate and difficult conditions, respectively.

As shown in Figure 6.2a, net productivity, evaluated in terms of total volume (cubic meters of loose chips produced) during chipping activity, was higher in easy and moderate accessibility, on average 85.71 m^3/h and 81.10 m^3/h, respectively, and lower in difficult conditions, on average 38.35 m^3/h. Efficiency in difficult conditions (Figure 6.2b) was 10% lower than moderate condition and 7% lower than easy conditions. On average, efficiency was 67.91%, 70.91% and 60.97%, respectively in easy, moderate and difficult condition of accessibility. Higher efficiency, close to 100%, was recorded in both easy and moderate conditions.



(**a**)



(**b**)

Figure 6.2 - *Variability of net productivity in cubic meters of loose chips produced per hour (**a**) and chipping efficiency considering all the operational and non-operational activity (**b**) classified by accessibility of the working site. The boxes include the variability of the data between the 25th and the 75th percentiles. The horizontal black line represents the median while the circle in dark red represent the mean.*

The highest efficiency is related to the working sites where NOD and travelling elements were not recorded probably due to working sites located at the terminal. As reported in Table 2, OD and NOD increase when the difficulty in the accessibility increases. Besides, time travelling inside working sites increases from easy to difficult accessibility. The frequent relocation could explain the higher value of time travelling and travel distance in difficult conditions of accessibility. As expected, travelling fuel consumption was higher in difficult working sites than in easy and moderate ones. This confirms, with the hight time travelling in difficult condition, the challenging task to chip in mountain areas.

Chipped volume and different accessibility to working sites significantly affect the total emission produced (R^2 = 0.43, $p < 0.001$). In particular, as reported in Figure 6.3, the predicted total emission (kg CO_2 eq) was higher in difficult conditions (1.25*volume chipped) than in easy (0.61*volume chipped) or moderate conditions (0.72*volume chipped).

Table 6.2 *- Descriptive statistics for time and fuel consumption based on Can-BUS system. OD: operational delay; NOD: non-operational delay*

		Easy		Moderate		Difficult	
	Unit	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Chipping	min	103.14	93.06	102.01	78.92	150.95	118.65
Travelling	min	3.02	3.42	5.99	7.91	9.21	11.18
OD	min	75.47	176.29	117.88	575.1	341.4	588.38
NOD	min	14.67	22.94	22.92	36.74	29.23	44.87
Travelling distance	km	0.55	1.09	1.17	1.95	1.29	1.9
Chipping fuel consumption	l/m³	0.41	0.25	0.46	0.27	0.59	0.34
Travelling fuel consumption	l/h	0.5	1.57	0.62	1.97	0.98	4.09
OD fuel consumption	l/h	4.76	7.02	12.99	6.52	3.11	5.26

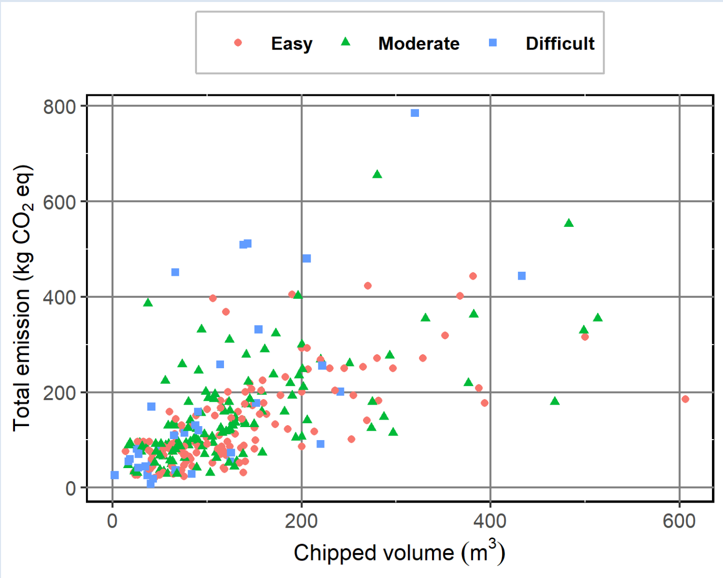


Figure 6.3 *- Total emission per working sites with the respect of chipped volume (cubic meters of loose chips produced) and accessibility*

6.5 Discussion

Time consumption of chipping operation and total emission in different working site classified by different conditions of accessibility was analysed. Similarly, Holzleitner et al. (Holzleitner et al., 2013) used the FMS and semi-automated method to monitor the supply processes of forest fuels. In this study, the data were analysed with the working site as observational unit. Isolating working activity, and related activity (travelling in working site, OD and NOD), our results show the effect of the accessibility on the efficiency and emission. Chipping activities in easy conditions, along primary public road, were the most effective method in terms of net productivity and total emission produced during all the operations (chipping, travelling and idle time while the engine is running). Chipping in mountainous conditions, especially with difficult accessibility and poor quality of road infrastructures, is a hard challenge and could lead to a decrease in efficiency of about 7–10% compared to easy and moderate conditions. Besides, the CO_2 eq emissions in these conditions can increase up to double the emission in easy conditions.

Higher variability in terms of chipping efficiency was recorded in difficult conditions of accessibility. These higher values were probably related to the higher OD, NOD and lower net productivity compared to easy and moderate accessibility. Analysing different chippers, Spinelli et al. (Spinelli and Visser, 2009) estimate, on average, total delay factor of 37.3% for chipping at the landing and 32.1% for chipping operation in the forest. Our results show higher efficiency for chipping operation in moderate conditions (70.91%) and lower in easy and difficult conditions (67.91% and 60.97%).

6.6 Conclusions

Chipping forest residues is considered an important economic and forest tending activity; besides the recovery of LQB after natural disturbances could reduce the risk of forest fires, diseases and pests (Vance et al., 2018). Environmental impact of recovery and chipping LQB are challenging operations especially in mountainous conditions, where the quality of road infrastructures (e.g., steep gradient and turning radius), quantity and distance between biomass piles and distance from the primary road network play an important role. Chipping in complex situations, as working sites along secondary forest road, lead to an increase in terms of CO_2 eq emission and a reduction of chipping efficiency. Time spent and travel distance are higher inside difficult working sites. Quantity and position of piles should be planned before starting the forest operations in order to favour the cooperation between the yarding contractor, chipping contractor and forest manager. Long term monitoring based on FMS has great potential and it is available for different truck-based models (Holzleitner et al., 2013). At present, additional information about wood quality and quantity need to be manually recorded by the operators and linked with machine activity parameters in order to better understand productivity and efficiency of chipping activity and fuelwood supply chain.

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Conflicts of Interest: The authors declare no conflict of interest.

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7 Paper VI - Efficiency Assessment of Fully Mechanized Harvesting System Through the Use of Fleet Management System

Narcis Mihail Bacescu [1], Alberto Cadei [1,*], Tadeusz Moskalik [2], Mateusz Wiśniewski [3], Bruce Talbot [4] and Stefano Grigolato [1]

[1] Department of Land, Environment, Agriculture and Forestry, Università degli Studi di Padova, Viale dell'Università 16, Legnaro, 35020 Padova, Italy; narcismihail.bacescu@phd.unipd.it (N.M.B.); stefano.grigolato@unipd.it (S.G.)
[2] Department of Forest Utilization, Institute of Forest Sciences, Warsaw University of Life Sciences—SGGW, Nowoursynowska 159/34, 02-776 Warsaw, Poland; tadeusz_moskalik@sggw.edu.pl
[3] Kłobuck Forest District, Zakrzewska 85 Str., 42-100 Kłobuck, Poland; mateusz.wisniewski@katowice.lasy.gov.pl
[4] Department of Forest and Wood Science, Stellenbosch University, Private Bag X1, Matieland, Stellenbosch, 7602, South Africa; bruce@sun.ac.za
* Correspondence: alberto.cadei@phd.unipd.it

7.1 Abstract

Nowadays the spread of precision forestry has led to the possibility of collecting data related to forest machines for an extended period and with enough precision to support decisions in the optimization of harvesting strategies in terms of technological and environmental efficiency. This study aims to evaluate the effective benefit of automatic data collection through the fleet management system (FMS) of two forest harvesters and two forwarders in pine forests in Poland. The study also aims to determine how the use of FMS can help forest companies to manage their fleet and take advantage of long-term monitoring. Focusing on performance indicators of fuel consumption and CO_2 emissions, as well as on the engine parameters from the Can Bus data, the exploration of data was performed following a Big Data approach, from the creation of an aggregate dataset, pre-elaboration (data cleaning, exploration, selection, etc.) using GIS and R software. The investigation has considered the machine productivity, in the case of the harvesters, and the specific fuel consumption of each machine studied, as well as the time used by each of them during the different working cycle activities and the total amount of timber processed. The main results indicate an average emission of 2.1 kg of CO_2 eq/m^3 for the harvesters and 2.56 kg of CO_2 eq/m^3 for the forwarders, which equates in total to 0.24% of the carbon stored in one cubic meter of wood.

Keywords: digital forestry; long-term monitoring; harvester; forwarder; CO_2 emissions; pine stands

7.2 Introduction

The improvement of harvesting methodologies plays an important role in the optimization of wood production in a context of sustainable forest management (Maesano et al., 2013). Different harvesting methods are applied according to forest site-specific conditions and degree of mechanization. The main different harvesting systems can be classified as fully mechanized, semi-mechanized or motor-manual harvesting system, according to the degree of mechanization used to carry out the different tasks involved in forest harvesting operations (Lundbäck et al., 2021). The most predominant systems nowadays are the fully and semi-mechanized systems. The fully mechanized systems are those based on the use of machines, such as harvesters and forwarders among others, that minimize manual labor. By increasing the level of mechanization for the development of the activities instead of manual labor, not only higher productivity but also greater operator safety is achieved(Sullman and Kirk, 2001b). Another side effect of the implementation of these systems is the possibility to fully record the wood extraction supply chain from the forest to the landing point, thanks to the on-board computers of the machines used. With the use of manual work, an automated monitoring of the chain flow is not always possible, and it is more costly to have such information available, as it implies the use of additional personnel. It also implies a higher probability of errors in the acquired data due to the human factor.

However, Cut to Length (CTL) systems with modern harvesters and forwarders constitute a fully mechanized harvesting system that offers the possibility to record a large range of the working and stand parameters. For example, instantaneous fuel consumption information, performance class of the engine, stem and individual log volumes and tree species can be recorded. Also, it can provide quantitative work features information, such as shift time consumption per processing of a production unit and constant records of geospatial coordinates of the machine, thus enabling the positioning of the recorded data (Prinz et al., 2018b).

The fully mechanized CTL system is based on the production of standardized assortments with previously specified lengths. These operations are usually carried by two machines, a harvester and a forwarder. It requires all the operations to be done at the stump site before the log transportation takes place from there to the forest road. CTL involves felling, delimbing (removing branches), topping (cutting the top of the stem at a specified diameter) and processing of the delimbed stems into log assortments by a harvester while a forwarder carries out the transportation of the assortments and their classification according to their purpose. When performed, through the use of harvesters and forwarders, this fully mechanized harvesting system (CTL system) requires less labor, less access road construction and fewer landing areas than other fully mechanized ground-based systems, such as whole-tree harvesting with feller-bunchers and skidders, and also leads to more efficient wood recovery (D. Tiernan et al., 2004). Before harvesters, chainsaws represented the most important work tools for the initial processing of the logs and timber production. Despite the increasing use of harvesters nowadays, chainsaws will still be used in the future, particularly for cutting trees of greater dimensions and in hardwood harvesting (Dvořák et al., 2011; Moskalik et al., 2017).

Operating forest machines is not only expensive, but the accurate monitoring of economic variables can be very difficult. Detailed machine data capture of economic variables within a forest enterprise can be used to support decision processes, especially accurate costing for new investments (Holzleitner et al., 2010). Time consumption and fuel consumption for forestry machines have been well-studied with the traditional aim of investigating the main factors affecting production and energy efficiency. Nowadays the reasons to conduct time studies have been broadened to include the developing and building of accurate models that can be utilized in different kinds of simulations that aim to find new, more efficient work methods, to optimize complete operations or to develop more efficient machines (Nurminen T, Korpunen H, 2006).

The increasing performance of the data acquisition, data processing and transmission due to the new technological advances (Industry 4.0) and the implementation of the principle of Precision Forestry (PF) make possible the monitoring and evaluation of forest resources, providing a tool for forest management to ensure the traceability of forest products (Kovácsová and Antalová, 2010; Lezier et al., 2019) and a tool to validate theoretical models regarding forest harvesting systems and efficiency (Bont et al., 2022). This technology allows decision-makers to have a detailed quali-quantitative characterization of wood resources, in both its geographical features and forest parameters. Such data platforms or the use of new harvesting machines, equipped with this technology, give the possibility to upload all data gathered continuously during the normal work condition and to request it as it is necessary. Therefore, when a fully mechanized harvesting system with modern machines is applied, it is typically possible to automatically record all the information related to the machine parameters and also characteristics of the harvested timber, such as metrics, species or position, from the stand to the roadside. Using the platform provided by the manufacturer, it is possible to visualize this information online (fuel consumption, productivity and position).

The most advanced forest machines, such as most heavy-duty construction, agricultural or transport vehicles, can be monitored through the use of specific Electronic Control Units (ECUs). The ECUs communicate the status and the parameters of the machines to the on-board computer (OBC) through the Controller Area Network (CAN-bus) and generally according to specific standard (e.g., SAE J1939). With the advance of automated data collection on the CTL system machines (Brewer et al., 2018), sensors and processors can communicate with the OBC, which represents the interface with the operators. In nearly all modern forest harvesters and processors, not only the machine engine and vehicle status are recorded but also the parameters of the harvesting and felling operations through the use of the Standard for Forest Machine Data and Communication (StanForD) (Olivera et al., 2014). As a consequence, the automation layer of the CTL machine passes through a CAN-bus system that connects all the related units, such as actuators, sensors and controllers, forming a distributed control system. The control system constantly produces and processes hundreds of signals related to the vehicle engine, transmission and harvester head performance and control, as well as the production parameters. The control system and the human operator interact through the on-board control system of the forest machine, which also produces standard production and performance data based on the measurements during the work.

Moreover, using the CAN-bus system in combination with Geographic Information Systems (GIS), forest contractors can track all vehicles from a central location through the fleet management system (FMS) (Ala-Ilomäki et al., 2020; Melander et al., 2019). This system allows technological efficiency to be maximized, productivity to be increased and safety for an organization’s vehicles and drivers to be improved. Usually, this is achieved using a combination of vehicle tracking (GNSS position), reporting on fuel consumption, monitoring of driver behavior and management of vehicle maintenance. In addition, the FMS can be used to investigate, and in a more accurate way, different aspects of forest operations, such as those related to the environmental performance (fuel consumption and CO_2 emissions, among others), which gain, day by day, more relevance both for the contractors as well as for the forest managers (Zhang et al., 2021). Despite the data availability, there have been few studies that focused on both technological and environmental efficiency.

Therefore, the objectives of this study are to analyze the technological and environmental efficiency of the CTL harvesting system based on the fleet management system. More specifically, the aims are to estimate the fuel consumption, CO_2 emissions and productivity, considering also the technological performance aspects, such as time consumption, and taking into consideration each machine type and each work element performed by them. In particular, technological and environmental efficiency will be analyzed in the contest of Scots pine forests in gentle terrain located in Poland.

7.3 Materials and Methods

7.3.1 Study Area and Machine Description

The working area is located in the State Forest District of KŁOBUCK (Poland). This is one of the districts situated in the northern part of the State Forest Regional Directorate (RDSF) of Katowice; however, it spreads between Silesian and a little area in Opole Voivodeships (Figure 7.1). The forests stand geographically between 50°48‘35” and 51°05‘57” Latitude and from 18°38‘30” to 19°15‘31” Longitude. Geologically, the Forest District is an upland sculpted to varying degrees, in the altitude range from 180 m.a.s.l. (Wąsosz Górny, Popów commune—Warta river level) up to 304 m.a.s.l. (Truskolasy, Węczyca commune). The terrain falls slightly from south to north, latitudinally crossed by the Warta valley, and then rises slightly from the northern borders reaching a height of 257 m.a.s.l. in Parzymiechy.

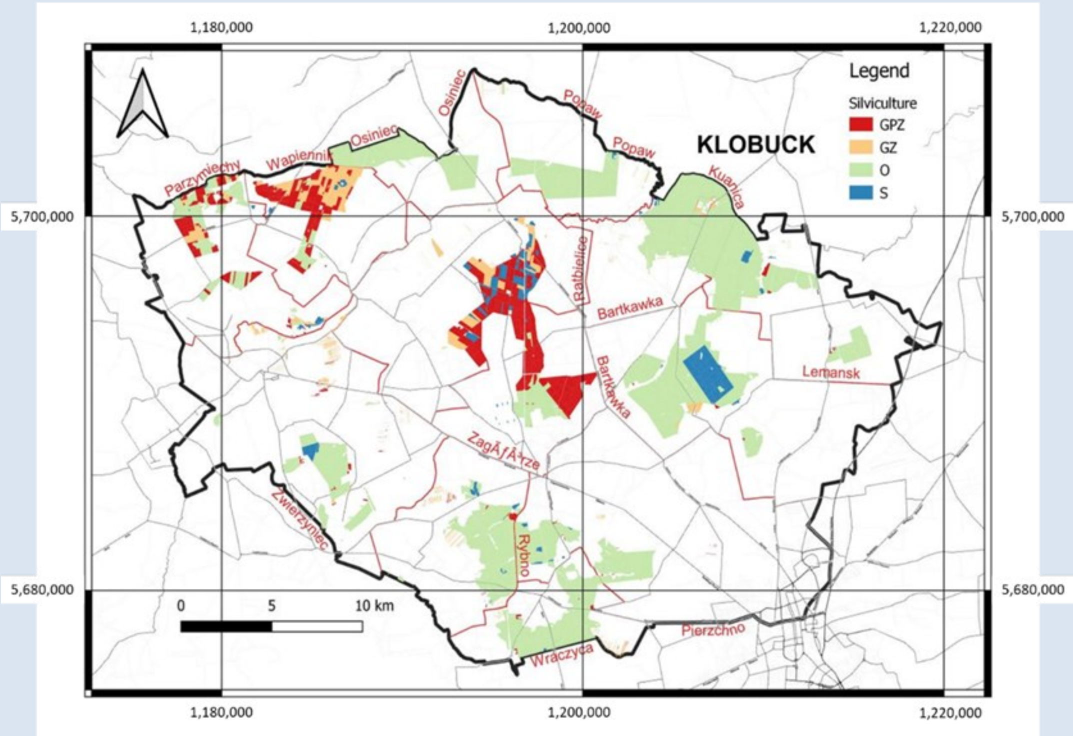

Figure 7.1 - Forest management units in the Kłobuck Forest District. GPZ—selection/clear cutting; GZ—clear cutting; O—multifunctional protective forests, S—special (protected) forests

The administrative area of the Kłobuck Forest District is 89,100 ha. This includes a forested area of about 21,800 ha, of which over 16,400 ha is managed by the Kłobuck Forest District. The forests' function, in addition to the production function, fulfils many non-productive tasks. The most important of them undoubtedly includes protective functions, among others, water supply and water balance control for the surrounding cities.

Scots pine (*Pinus sylvestris*; L.) is the dominant species on almost 85% of the area, pedunculate oak (*Quercus robur*; L.) and sessile oak (*Quercus petraea Matt.*) at just over 5% and, of the other species, none exceeds 5%. The same percentages can be assumed for volume as well. In the stands of the Kłobuck Forest District, foreign species are visible, but they achieve no significant shares: black pine (*P. thunbergii*; Parl.), Weymouth pine (*Pinus strobus*; L.) and red oak (*Quercus rubra;* L.); as dominant species, they occupy only 0.5% of the forested area in total. Single species and double species stands cover more than one-half (58%) of the forested area. This is likely to happen since the dominant species is the Scots pine, which naturally tends to create one-leveled, single-story stands.

Two harvesters and two forwarders were used during CTL logging operations. The harvesters were two 200 kW John Deere 8-wheeled 1270G models with rotating and self-leveling cabin: One (H1) was equipped with the H414 harvesting head, and the other (H2) was equipped with the H480C Harvesting Head (Table 7.1). The forwarders were a 136 kW John Deere 8-wheeled 1210E (F1) and a 164 kW John Deere 8-wheeled 1510G model (F2) with rotating and self-leveling cabin (Table 7.2). The harvesters and the forwarders were provided with Windows-based TimberMatic™ (John Deere, Moline, IL, USA) as a control system. Both harvesters were equipped with EU Stage IV approved engines; as for the forwarders, the forwarder F1 was equipped with EU Stage IIIB complying requirements engine, and the forwarder F2 engine was certificated as EU Stage V.

These stages were set by the European Union since 1997 in order to regulate diesel engines' emissions in off-road machines. EU Stage IV was established in 2005, and apart from amending the previous stages, it also introduces restrictions regarding particle number (PN) emission limit that has to be under 0.025 g/kWh. This policy was designed to force the use of diesel particulate filters. EU Stage IV also includes a limit for ammonia emissions, which must not exceed a mean of 25 ppm over the test cycle.

EU Stage IV differs from EU Stage IIIB for covering different types of engines, but it applies the same emissions standard as EU Stage IIIB. EU Stage V introduces a new mass-based limit for PN emissions that aims to ensure the use of a highly efficient particle technology on the certificated engines. All these stages´ emissions limits are listed in Appendix A.1. These standards only cover the exhaust emissions of the engine prior to its passage through the exhaust filters, thus the CO_2 emission (the most relevant of the Greenhouse Gases—GHGs) at this phase can only be found as CO and not CO_2. Therefore, the comparison between emitted CO_2 and emitted CO is not possible in a reliable way.

The operators have more than 10 years of experience, except in the case of one forwarder operator, who had 2 years of experience, and they work organized in double shifts. Typically, the harvesters and the forwarders work in pairs, and each forwarder extracts the timber stacked in the forest by the harvester. In this study, forwarder F1 worked paired with harvester H1, and forwarder F2 worked paired with harvester H2.

The first team composed by H1 and F1 was performing thinning operations; meanwhile, the second team, composed of H2 and F2, was performing the final felling. Moreover, harvester H1 and forwarder F2 were equipped with John Deere (John Deere, Moline, IL, USA) Intelligent Boom Control (IBC), which automatize the movements and trajectory of the boom in order to allow the operator to focus on the grapple instead of the movements of the crane´s joints.

Table 7.1 *- Harvesters' specification*

Harvester		**H1**	**H2**
Model	-	John Deere 1270G	
Engine	-	John Deere PowerTech™ Plus 6090	
Emission standards		EPA FT4/EU Stage IV	
Power	kW (hp)	200 (268) *	
Transmission	-	Hydrostatic-mechanical, 2-speed gearbox	
Wheel number	n°	8	
Tire size	-	710/45-26.5	
Base Carrier Length	mm	7927	
Width	mm	2960	
Ground Clearance	mm	654	
Weight with harvester head		22,200	
Fuel Tank	L	450	
Crane specifications			
Crane Model	-	Waratah CH7117	
Gross lifting moment	kNm	199	
Max load	kg	1150	
Maximum boom reach	m	10	
Weight	kg	3200	
Harvester head specifications			
Model	-	H414	H480C
Age Harvesting Head	-	2018	2016
Felling Diameter	mm	620	710
Delimbing knife	n°	4 moving, 2 fixed	
Delimbing Diameter	mm	430	460
Delimbing Feed Force	kN	27	30
Max Feeding speed	m/sec	5.3	5.3

* at 1900 rpm.

Table 7.2 *- Forwarders' specification*

Forwarder		F1	F2
Model	-	John Deere 1210E	John Deere 1510G
Engine	-	John Deere PowerTech™ Plus 6068	John Deere PowerTech™ Plus 6068
Emission standards	-	EPA IT4/EU Stage III B	EPA FT4/EU Stage V
Power	kW (hp)	136 (183) *	164 (220) *
Transmission	-	Hydrostatic-mechanical, 2-speed gearbox	
Ground clearance	Mm	670	660
Wheel number	n°	8	8
Tire size	-	710/45-26.5	
Steering angle	°	44	44
Weight empty	T	18.1	18.2
Load capacity	T	13	15
Crane specifications			
Boom crane model	-	Waratah CF710	Waratah CF785
Gross lifting moment	kNm	125	125
Max load	kg	810	985
Maximum boom reach	m	10	8.5
Weight	kg	1735	1630

* at 1900 rpm.

7.3.2 Data Collection

The work measurements were conducted through a follow-up study, where data were automatically recorded by the forest machines OBCs during working activity. To better analyze and understand the performance of the machines in terms of efficiency, work activity was divided into different work elements (Table 7.3).

Table 7.3 *- Different work elements considered in the study*

Harvesters		Forwarders	
Activity	**Work Element**	**Activity**	**Work Element**
Tree cutting and felling	Process	Driving loaded	Drive loaded
Delimbing and bucking to length		Driving unloaded	Drive unloaded
Moving to the next tree	Preparation	Loading	Loading
Other	Other	Unloading	Unloading

Since the involved machines are from the same manufacturer, to achieve the aim of the study, the official system of the company, called JDlink™ (John Deere, Moline, IL, USA) was fully exploited. JDLink™ is John Deere's telematics system that connects all make/model machines produced by this company working in the field with the office and mobile devices. This is a wood procurement systems product, used for production, preparation and planning or feedback analysis of the data collected during production or for direct communication with the production so intended for desktop designated for this task (Figure 7.2).

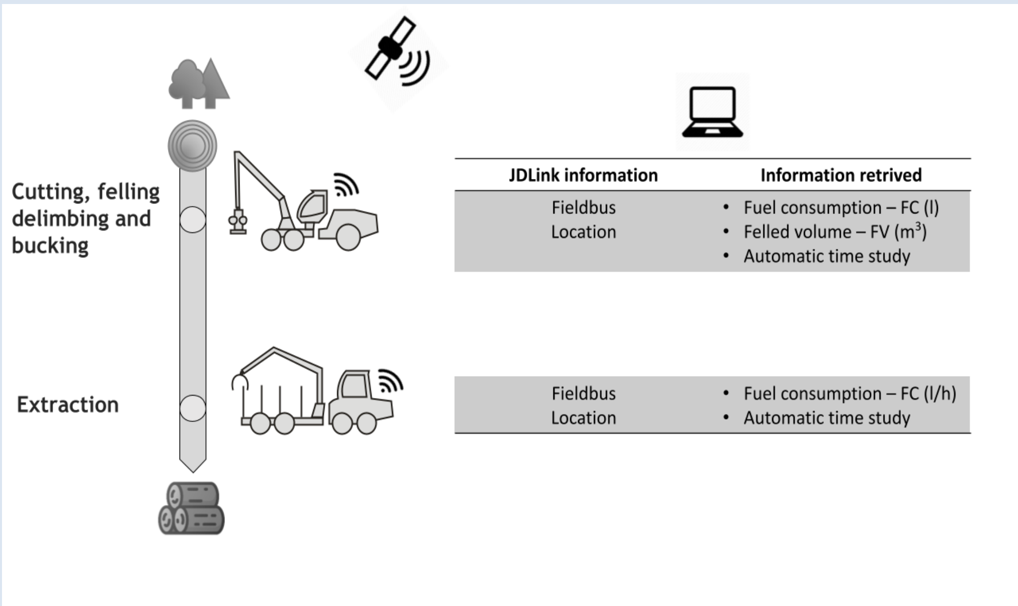

Figure 7.2 *- Schematic visualization of the wood procurement system JDlinkTM*

From JDLink™, geospatial and fieldbus data was available from September 2018 to January 2020 with hourly-shift level, which was the higher data frequency available. Stand information was downloaded from Polish Forest Data Bank (Bank Danych o Lasach). Geospatial information, latitude and longitude, were recorded by the Global Navigation Satellite System (GNSS) receiver. The fieldbus data related to the vehicle engine parameters, transmission and harvester head performance (Can-BUS and StanForD data) were collected by the Timberlink® software, which controls the OBC. This information, stored in the OBC of each machine, was automatically uploaded to the JDLink™ portal. The most important parameters considered in this study, therefore, were as shown in Appendix A.2.

Several steps occurred before having the complete dataset ready for further analysis. Since all the data of interest were stored in separate files, there was the need to process the GNSS file obtained by download from JDLink with hourly resolution, containing stand information and the file in a unique complete dataset. Merging in R needs a common key variable, which was resolved with the "setkey()" function, using as condition the nearest time between the two datasets for every day, since the aim was to pair columns of both datasets by the same moment of recording. In this way, it is possible to know exactly where a machine has worked with an hourly precision.

7.3.3 Data Analysis

Time Consumption and Productivity Analysis

To obtain the management planning, forest administrative borders and stand parameters, the daily harvester positions were filtered in order to remove the non-working location by the field bus data using QGIS 3.10 A Coruña version and R core ™ 2021 software. The obtained dataset contains all the information related to the harvester position sampled once per hour, and the timber felled, delimbed and bucked in the forest summed each hour. In fact, the analyzed work system represents a CTL system where the two harvesters deal with felling, delimbing and bucking in the forest. Consequently, the two forwarders had the task of extracting the timber from the forest to the roadside. Since the forwarder location was saved once per hour, as the harvesters, but considering that the forwarders cross different stands during the timber extraction, it was not possible to merge the field bus with the correct stand (where the forwarder loads the timber) due to the low frequency of the data acquisition. Thanks to the fact that harvesters and forwarders work in pairs and the only task of the forwarder was to extract timber, we assumed that the extracted volume is equal to volume stacked in the forest by the harvester (58,160.20 m^3). Due to the exact geospatial information of the harvester, the related fieldbus information (time study, fuel consumption, processed volume, etc.) was also analyzed. As a result, a database that could be characterized as big data was obtained.

To analyze the obtained dataset and the interaction between the different working factors recorded by the fieldbus system, inferential statistics were used, assuming the hourly observation as the observational unit. Due to the wide range of variation of the data and in order to reduce that variation, the considered observational unit was decided to be the workday. In the case of the forwarders, the range of variation was even higher, thus the workday in this case was defined as those days on which more than 6 h of productive machine work were recorded.

However, after data processing, the data proved not to be normally distributed, therefore an inferential statistical analysis would not be the most appropriate or accurate approach to the analysis of the data set. Instead, the non-parametrical, two-sample Mann–Whitney U Test was performed at 95% confidence interval for the median. The test was carried out both intergroup and intragroup (including time and fuel consumption); this means that the test was conducted to analyze the differences between the various activities performed by each machine as well as the differences between the same activities performed by the two different machine models in each case (harvester H1 in contrast to harvester H2 and forwarder F1 in contrast to forwarder F2).

Efficiency Analysis

Fuel consumption is defined as the amount of fuel in liters consumed by a machine during one working hour, and its measurement unit typically is expressed as l/h. In emission analysis, fuel consumption is indeed an important value when CO_2 emissions are computed indirectly (Cosola et al., 2016). Carbon dioxide equivalent emissions (kg CO_2 eq) were calculated applying an emission factor of 2.61 to each liter of fuel consumed (De la Fuente et al., 2017).

Forwarders' and harvesters' fuel consumption is traditionally measured using a mass flow meter, or the consumed fuel is determined by measuring the fuel input during the refilling activity. However, in this study, the CAN bus acquiring data system was used in order to achieve a higher accuracy of the measurement of fuel consumption (Eriksson and Lindroos, 2014) and to differentiate the fuel consumption variation among the different activities performed.

7.4 Results

During the data acquisition and after the data analysis, the result dataset contains in the case of the harvesters a total of 2249.38 time-related observations (parameters hourly recorded), which converted to the observational units means 433 observations. Regarding the result dataset related to the analysis of the forwarders' performance, the total amount of time-related observations was 3764.67. This number of observations translates to 245 observational units. Analyzing the fuel consumption, during the 678 days of working time considered in this study, a total of 46,114.58 l of fuel was consumed by the four machines (two harvesters and two forwarders). This fuel consumption leads to a total of 120,359.06 kg of CO_2 eq emissions. Furthermore, considering the total amount of processed wood recorded by each harvester (30,168.27 m^3 by H1 and 25,155.81 m^3 by H2), the average volume of fuel consumed by the first team composed of harvester H1 paired with forwarder F1, per product unit was 0.74 l/m^3, and the CO_2 eq produced per product unit was 1.92 kg CO_2 eq/m^3. Regarding the second team composed of harvester H2 and forwarder F2, a total of 0.95 l/m^3 were consumed, producing a total of 2.48 kg CO_2 eq. In addition, from the dataset, it was also possible to extract the average productivity of the harvesters, which in the case of H1 was of 26.63 m^3/h and in the case of H2 was of 22.17 m^3/h. The productivity of the forwarders was not possible to calculate since there was no possibility to measure their loads.

7.4.1 Harvesters' Analysis

The descriptive statistics of the work element of the harvesters are shown in Tables 7.4 and 7.5. Over 39% of the time spent was related to time process operation while 35% to 40% of the remaining time was preparation time. The work element related to non-productive time ranged from 21% to over 24% of the total time.

Table 7.4 *- Time distribution per working element of harvester H1 and H2*

Machine Type	Work Element	n° obs	Total Time		Mean Time Per Day	SD
			min	%	min/Day	min/Day
H1	Preparation		23,830.40	35.41	117.39	43.91
H1	Process	203	26,782.09	39.80	131.95	55.47
H1	Other		16,677.77	24.78	82.16	35.89
H2	Preparation		26,741.46	39.52	116.25	52.28
H2	Process	230	26,652.89	39.38	115.89	55.82
H2	Other		14,278.46	21.10	62.08	30.85

The fuel consumption rates according to the two different models of machines studied and their working elements are shown in Table 5. The total amount of fuel consumed during the 2249.38 h of observations was 35,527.23 l for both machines. 17,304.72.64 l were consumed by the harvester H1, with an average fuel consumption rate of 15.43 l/h, and 18,222.51 l was consumed by the harvester H2, with an average fuel consumption rate of 16.16 l/h. The most fuel-demanding activities correspond to the preparation and processing parts of the work cycle with approximately 93% of fuel consumption. The remaining 7% corresponds to other times such as operators' breaks, machines' repair and set up, logistics, etc.

Considering an average volume of trees for each stand in which the harvesters worked, the average fuel consumption per cubic meter can be calculated. In the case of harvester H1, the fuel consumption per cubic meter of logs processed was 0.571 l/m^3 and in the case of harvester H2 the fuel consumption per cubic meter was 0.72 l/m^3. In terms of CO_2 eq emissions, a total of 92,726.07 kg was produced by the harvesters. Harvester H1 produced a total of 45,165.32 kg of CO_2 eq, and harvester H2 produced a total of 47,560.75 kg of CO_2 eq.

Table 7.5 *- Fuel consumption and CO2 eq. emissions of harvesters H1 and H2*

Machine Type	Work Element	n° obs	Total Fuel Consumption	Mean Fuel Consumption per Work Element		SD	Mean CO_2 eq. Emissions per Hour of Work Element	Mean Fuel Consumption per Hour of Work	Mean CO_2 eq. Emissions per Hour of Work
			l	%	l/h	l/h	kg/h	l/h	kg/h
H1	Preparation		7303.98	42.21	18.39	1.51	47.66		
H1	Process	203	8827.63	51.01	19.78	1.3	51.34	15.43	40.27
H1	Other		1173.11	6.78	4.22	1.26	4.25		
H2	Preparation		7951.52	43.63	17.84	1.6	46.35		
H2	Process	230	9138.12	50.15	20.57	1.43	53.27	16.16	42.17
H2	Other		1132.87	6.22	4.76	4.34	8.61		

Regarding the non-parametrical statistical analysis of the time and fuel consumption differences between harvester H1 and H2 (intergroup), and the time and fuel consumption differences between the work elements of each of them (intragroup), there were found significant differences in all the compared pairs of data, except for the interaction intergroup between the time consumption of the processing work element among the H1 and H2, and the interaction intragroup between the time consumed by H2 performing preparation and processing work elements. The p-values at 95% confidence interval for the median of all the comparisons performed can be found in Tables 7.6 and 7.7.

Table 7.6 *- Harvesters intergroup p-value of Mann–Whitney U test between different time consumption*

Work Elements Compared	*p*-Value of Time Consumption Comparison	*p*-Value of Fuel Consumption Comparison
Preparation	<0.000	<0.000
Process	0.87	0.0020.
Other	<0.000	0.02

Table 7.7 *- Harvesters intragroup p-value of Mann–Whitney U test between different time consumption*

Machine Type	Work Elements Compared	*p*-Value of Time Consumption Comparison	*p*-Value of Fuel Consumption Comparison
H1	Preparation vs. Process	<0.000	<0.000
H1	Preparation vs. Other	<0.000	<0.000
H1	Process vs. Other	<0.000	<0.000
H2	Preparation vs. Process	0.6	<0.000
H2	Preparation vs. Other	<0.000	<0.000
H2	Process vs. Other	<0.000	<0.000

7.4.2 Forwarders' Analysis

The descriptive statistic regarding the time consumption of the work element of the forwarders is shown in Table 8. Based on the descriptive statistics, the percentage of time spent driving loaded (14% of the working time for each forwarder) was lower than the time spent driving unloaded (18 and 20% of the working time for each forwarder); however, analyzing the non-parametric tests performed (Tables 9 and 10), it can be observed that the differences regarding the time consumption for both forwarders (F1 and F2) performing the mentioned work elements (drive unloaded and drive loaded) is not significant at 95% confidence interval for the median (*p*-values of 0.1 and 0.8, respectively). Furthermore, in the case of the forwarder F1, in both work elements (drive loaded and drive unloaded) are not significant differences at 95% confidence interval for the median (*p*-value of 0.07). The time spent loading varies between 45% and 42% of the total working time whereas the time spent unloading was 23% of the total working time. Also, a complementary analysis was performed in order to have a broader idea about the working productivity and efficiency during the time that the data was recorded. A theoretical cycle was simulated assuming an extraction distance of 350 m (700 m driven per simulated working cycle) and the resulting number of simulated cycles per observational unit (work days with at least 6 h of activity) considering the total distance driven by the forwarders included 17 cycles for the F1 forwarder and 15 cycles for the F2 forwarder (standard deviation of 7 and 6, respectively).

Table 7.8 *- Time distribution per work element of forwarder F1 and F2*

Machine Type	Work Element	n° obs	Total Time		Mean Time	SD
			min	%	min	min
F1	Drive Loaded	128	11,607.0	13.90	90.68	42.86
F1	Drive Unloaded		15,231.0	18.24	118.99	57.32
F1	Loading		37,419.0	44.81	292.34	121.07
F1	Unloading		19,252.2	23.05	150.41	61.05
F2	Drive Loaded	117	9462.6	14.16	80.88	39.41
F2	Drive Unloaded		13,638.0	20.41	116.56	59.66
F2	Loading		28,318.2	42.38	242.04	106.28
F2	Unloading		15,396.6	23.04	131.59	53.61

The distribution of fuel consumption between the different work activities of the forwarders is shown in Table 7.11. The total fuel consumption of both forwarders was 10,587.35 l. Forwarder model 1210E consumed a total of 4948.00 l, with an average fuel consumption of 9.27 l/h. The forwarder model 1510G consumed a total of 5639.35 l, with an average fuel consumption of 11.75 l /h. The most demanding fuel activities for both machines were driving loaded, with approximately 31% of the fuel consumption. The average value of fuel consumption per product unit was 0.19 l/m^3, more precisely forwarder F1 consumed an average of 0.16 l/m^3, and forwarder F2 had an average fuel consumption per product unit of 0.22 l/m^3. Regarding the CO_2 eq emissions of both forwarders, a total of 27,632.98 kg of CO_2 eq was produced. Forwarder type 1210E produced a total of 12,914.28 kg of CO_2 eq, and forwarder type 1510G produced 14,718.70 kg of CO_2 eq.

Performing the non-parametrical statistical Mann–Whitney U test of the fuel consumption differences (Tables 7.9 and 7.10) between the different work elements performed by forwarders F1 and F2 (intragroup) and the time and fuel differences between the same work elements performed by each of them (intergroup), significant differences were found in all comparisons.

Table 7.9 *- Harvesters intergroup p-value of Mann–Whitney U test between different time consumption*

Work Elements Compared	*p*-Value of Time Consumption Comparison	*p*-Value of Fuel Consumption Comparison
Loading	<0.000	<0.000
Unloading	<0.000	<0.000
Drive Loaded	0.80	<0.000
Drive Unloaded	0.10	<0.000

Table 7.10 *- Harvesters' intragroup p-value of Mann–Whitney U test between different time consumption*

Machine Type	Work Elements Compared	*p*-Value of Time Consumption Comparison	*p*-Value of Fuel Consumption Comparison
F1	Loading vs. Unloading	<0.000	<0.000
F1	Loading vs. Drive Loaded	<0.000	<0.000
F1	Loading vs. Drive Unloaded	<0.000	<0.000
F1	Unloading vs. Drive Loaded	<0.000	<0.000
F1	Unloading vs. Drive Unloaded	<0.000	<0.000
F1	Drive Loaded vs. Drive Unloaded	0.07	0.008
F2	Loading vs. Unloading	<0.000	<0.000
F2	Loading vs. Drive Loaded	<0.000	<0.000
F2	Loading vs. Drive Unloaded	<0.000	<0.000
F2	Unloading vs. Drive Loaded	<0.000	<0.000
F2	Unloading vs. Drive Unloaded	<0.000	<0.000
F2	Drive Loaded vs. Drive Unloaded	<0.000	0.004

Table 7.11 *- Fuel consumption and CO2 eq. emissions of forwarders F1 and F2*

Machine Type	Work Element	n° obs	Total Fuel Consumption		Mean Fuel Consumption	SD	Mean CO_2 eq. Emissions	Mean Fuel Consumption per Hour of Work	Mean CO_2 eq. Emissions per Hour of Work
			l	%	l/h	l/h	kg/h	l/h	kg/h
F1	Drive Loaded	128	1557.14	31.47	12.17	3.03	31.76	9.27	24.2
F1	Drive Unloaded		1251.00	25.28	9.77	2.36	25.50		
F1	Loading		1143.15	23.10	8.93	1.03	23.31		
F1	Unloading		996.71	20.14	7.79	0.92	20.33		
F2	Drive Loaded	117	1723.97	30.57	14.73	3.27	38.45	11.75	30.67
F2	Drive Unloaded		1280.96	22.71	10.95	2.18	28.58		
F2	Loading		1357.05	24.06	11.6	1.29	30.28		
F2	Unloading		1277.37	22.65	10.92	1.15	28.50		

7.5 Discussion

In order to meet EU targets for energy savings and GHG emissions reduction, and to improve the CO_2 sink role of forest ecosystems, it is necessary to understand and quantify the different factors influencing forest management. In this study, relatively new technological methods were used to quantify key aspects of forest operations management, such as productivity, time efficiency, fuel consumption and GHG emissions.

Regarding the productivity of the system analyzed in the case of the harvesters, the total productive time (preparation and process) represented almost 80% of the total time. This value is approximatively the same as other values (approx. 79%) reported in similar studies for final felling and thinning operations (Eriksson and Lindroos, 2014). It is interesting to note that, in a different study where the productivity of the CTL system was analyzed in aged oak coppice stands (Suchomel et al., 2011), the processing time accounted for 39.7% of the total working time (including also delays and other non-productive times), which is close to the ones reported in this study (approx. 40% for both harvesters). Analyzing the time share between the different work elements of H1 compared to H2, there are significant differences between them, except for the processing work element, in which case no significant differences were found. Since both harvesters (H1 and H2) were the same machine model, and significant differences were found between the fuel consumption during the performance of all work elements, it can be deducted that the harvesting operation method carried out in that environmental condition (thinning operation versus final felling) have a significant influence in the fuel consumption but not in the time distribution regarding the processing work element. In addition, with regard to H2 time distribution of the processing and preparation work elements performed during the final felling, no significant difference was found, although the productivity of H2 (22.17 m^3/h) was lower than the productivity of H1 (26.63 m^3/h) and the fuel consumption, per product unit, was higher in the case of the H2 (0.72 l/m^3) than in the case of H1 (0.57 l/m^3). This leads to the inference that a higher time share of the preparation work element incurs in a lower productivity as well as in a higher fuel consumption.

Compared to other studies (Gagliardi et al., 2020; Pandur et al., 2018), all the values reported in this study regarding the time share of the forwarders' work elements are under the range of the values reported in their results. In the comparing studies, the percentage of time that the forwarder spends on driving loaded range between 8% and 20% (approx. 14% in this study). As for the share of time that the forwarder spends driving unloaded, the percentages reported by the studies ranges between 12% and 17% (18% per F1 and 20% per F2 in this study). Regarding the time loading, the values reported by other studies ranges between 30% and 55% of the productive time, while in this investigation the values reported for this work element were 45% for F1 and 42% for F2. Also, the share of the time spent unloading in those cases varies between 20% and 30% of the total productive time, and in this study, a time share of 23% was reported.

Moreover, the fact that, in this research, both forwarders recorded were different and were working on different stands (thinning and final felling,) but with the same species composition, and yet, there was no significant difference between the time share driving loaded or driving unloaded work element between F1 and F2 (despite the different operator's experiences). Between driving loaded or unloaded work element in the case of forwarder F1, it means that the time efficiency of a forwarder depends on the ratio machine power, stand parameters such as the DBH and working conditions (e.g, extraction distance, slope). In terms of efficiency, the fuel consumption rates in most cases base their estimates on previous calculations or life cycle assessments; however, over the last few years, more and more empirical methods have been used considering real data, as is the case in this study.

Considering the case of the harvesters, the average fuel consumption values reported in this study per working hour and per product unit (15.43 l/h and 0.57 l/m^3 by H1 and 16.16 l/h and 0.72 l/m^3 by H2) are under the range reflected in other articles (Apafaian et al., 2017; Haavikko et al., 2022; Lijewski et al., 2017). Similar studies report an average fuel consumption per product unit ranging from 0.6 l/m^3 in thinning operations until 1.8 l/m^3 in final fellings. Nevertheless, the number of studies in which the fuel consumption of harvesters is reflected using direct measurement methods is limited. If, furthermore, it is desired to study the relationship between each activity of the work cycle performed by the harvester with its specific fuel consumption, the related publications are even more reduced.

The related CO_2 emissions recorded were of 40.27 kg CO_2 eq./h in the case of H1 and 42.17 kg CO_2 eq./h in the case of H2, and 1.49 kg CO_2 eq./m^3 were produced by H1 and 1.88 kg CO_2 eq/m^3 by H2. Since the calculation of the CO_2 emissions is performed in an indirect manner (using 2.61 as converting coefficient) from the fuel consumption, it is assumed that the emissions values are also in the same ranges of variation as those ones recorded in similar studies mentioned above, nevertheless different conversion methods and coefficients are used to estimate the machine emissions, thus the final values maybe not completely similar.

Regarding the forwarders' fuel consumption and CO_2 eq emissions, the values reported per product volume are under the ranges of values reported by similar studies (Manner et al., 2013; Nurminen T, Korpunen H, 2006). In the comparing studies the fuel consumed per product unit and the fuel consumed per hour of productive time are higher than in this research, achieving, in those cases values of 1.18 l/m^3 and 17.36 l/h in one case and 0.45 l/m^3 and 18 l/h. However, the higher fuel consumption values are justified due to the different characteristics of the harvesting operation (extraction distance higher than 2 km) or due to the different harvesting machines' characteristics used in those cases (more than 200 kWh in comparison with approx. 150 kWh of the forwarders studied in this case).

Regarding the CO_2 emission, in the case of the forwarders, 24.2 kg CO_2 eq./h and 30.67 kg CO_2 eq./h were estimated per productive working hour. As for the emissions related to the production unit, 0.49 kg CO_2 eq./m^3 and 0.42 kg CO_2 eq./m^3 were estimated in the case of the forwarders (F1 and F2, respectively).

In this case, the number of studies related to forwarder performance parameters and their interaction with stand characteristics was higher than for harvesters. Also, in the case of the forwarders, the working cycles and their different parts have been studied in more depth in similar studies, and their results, to a large extent, coincide with those of this study.

7.6 Conclusions

The fleet management system integrated with GIS analysis and the use of coding software like R core™ 2021, in this case, has proven to be an exceptionally useful tool able to improve the decision-making process, both for forest managers and forest contractors. In fact, both data collection and analysis process showed is an easy-to-use tool to evaluate the forest machines. In addition, the implementation of this approach allows for the detection of not only the possible weaknesses when a CTL system is performed, and its consequent decrease in productivity and efficiency terms, but it also allows to quantify those decreases and to detect in which part of the system they may occur.

Moreover, this approach is fundamental to achieve a higher sustainability and lower environmental impacts in forest operations through the possibility to design beforehand the best operational plan of the harvesting process and reduce in this way the emissions and the environmental impact (soil degradation, GHG emissions and vegetation damage among others).

In this study, it has been possible to detect, for example, that comparing to other similar studies, the fuel consumption rates according to the harvesting operation (thinning or final felling) was higher when final felling harvesting operations were performed. Moreover, this variation is a consequence of higher fuel rates while performing those operations compared with performing thinning operations. Also, the time share of the most fuel consuming work elements increases in the case of final felling.

However, there is still a knowledge gap related to the way in which the different aspects involved in forest operations management interact with each other. Factors such as those related to the forest stand, environmental and terrain conditions, or the characteristics of the various machines used, play a fundamental role in improving forest management and therefore forest ecosystems.

Even though these factors have been studied over the years from various points of view, it is essential to also analyze the interaction that takes place between these factors and how these interactions and the variations in the values of the different parameters affect the development of forestry operations. The availability of geospatial information related to forest plan can substantially give historical information of the forest structure. This information merged with timber harvesting operations can lead to a quantification of the impact of forest operations.

In addition, data from fully mechanized harvesting systems proves to give the possibility to completely and easily collect the log data and related forest machine emission from the forest to the landing point. Although, in order to increase the accuracy of the data, the data acquiring process has to be performed at a higher frequency (shorter time between sampling) and/or the samples have to contain more information regarding the working parameters. In order to achieve this, a time study using video records and analysis, is usually performed; however, this method is not feasible in the case of studies that consider a wilder variation on the parameters that influence harvesting operation, due to the broad period of time covered by them. Further study needs to show the implication of the use of this data in order to better understand the environmental impact, in term carbon balance, of the wood extracted. Furthermore, sensorization of a non-fully mechanized system can substantially improve both data acquisition and the elaboration process to easily quantify the environmental impact of timber harvesting operations using different harvesting systems.

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7.7 Appendix A

Appendix A.1

Table A1. EU Stage IIIB, EU Stage IV and EU Stage V emissions limits.

Stage IIIB

Cat.	**Net Power**	**Date †**	**CO**	**HC**	**HC+NOx**	**NOx**	**PM**
	kW		**g/kWh**				
L	130 ≤ *P* ≤ 560	2011.01	3.5	0.19	-	2	0.025
M	75 ≤ *P* < 130	2012.01	5	0.19	-	3.3	0.025
N	56 ≤ *P* < 75	2012.01	5	0.19	-	3.3	0.025
P	37 ≤ *P* < 56	2013.01	5	-	4.7	-	0.025

Stage IV

Cat.	**Net Power**	**Date**	**CO**	**HC**	**NOx**	**PM**
	kW		g/kWh			
Q	130 ≤ *P* ≤ 560	2014.01	3.5	0.19	0.4	0.025
R	56 ≤ *P* < 130	2014.1	5	0.19	0.4	0.025

Stage V

Category	**Ign.**	**Net Power**	**Date**	**CO**	**HC**	**NOx**	**PM**	**PN**
		kW		g/kWh				1/kWh
NRE-v/c-1	CI	*P* < 8	2019	8	7.50 [a,c]		0.40[b]	-
NRE-v/c-2	CI	8 ≤ *P* < 19	2019	6.6	7.50 [a,c]		0.4	-
NRE-v/c-3	CI	19 ≤ *P* < 37	2019	5	4.70 [a,c]		0.015	1×10^{12}
NRE-v/c-4	CI	37 ≤ *P* < 56	2019	5	4.70 [a,c]		0.015	1×10^{12}
NRE-v/c-5	All	56 ≤ *P* < 130	2020	5	0.19 [c]	0.4	0.015	1×10^{12}
NRE-v/c-6	All	130 ≤ *P* ≤ 560	2019	3.5	0.19 [c]	0.4	0.015	1×10^{12}
NRE-v/c-7	All	*P* > 560	2019	3.5	0.19 [d]	3.5	0.045	-

† Dates for constant speed engines are: 2011.01 for categories H, I and K; 2012.01 for category J. [a] HC+NOx; [b] 0.60 for hand-startable, air-cooled direct injection engines; [c] A = 1.10 for gas engines; [d] A = 6.00 for gas engines.

Appendix A.2

Table A2. The most important parameters recorded and considered in this study.

Dataset Name	Explanation	Unit
CodeHrData	Date	yyyy-mm-dd hh-mm-ss
DistHighGear	High Gear Distance	Km
EngTimeLoadMax	Time of engine at maximum load	H
EngTimeLoadMin	Time of engine at minimum load	H
Mac_type	Machine name	/
AvgFuelRate	Average fuel consumption rate	l/h
DistLowGear	Low gear distance	Km
EngTimeLoadMedium	Time of engine at medium load	H
FuelConsumed	Tot fuel consumption	l/h
FuelDPrep	Fuel consumption during the processing phase	l/h
FuelVolm3Standard	Fuel consumption l/m^3	l/m^3
MachTimeFunctMinHighReg	Function at low regimes and high rpm	H
MachTimeRegMinHighReg	Time of machine status at high regime	H
ProdVol_m3h	Productivity	m^3/h
TimehPrep	Time spent on preparation	H
TreeCountStandard	Number of cut trees	/
TreeVolStandard	The volume of cut trees	m^3
MachTimeTOT	Sum of all machines status times	H
Year_Month	Date	yyyy-mm
H	height	M
Vol	Parcel stock m^3	m^3
Height	height	M
EngTimeRegEngMin	Time of engine at low rpm	H
FuelDOther	Non-productive fuel consumption	l/h
FuelDProcess	Processing fuel consumption	l/h
MachTimeEngineStop	Machine stopped	H
MachTimeFunctMinLowReg	Function at low regimes and low rpm	H
MachTimeRegMinLowReg	Time of machine status at low regime	H
TimehOther	Non-productive time	H
TimehProcess	Processing time	H
TreeVolAvg_m3	The average volume of cut trees	m^3
EngLoadTimeTOT	Total time at the engine on	H
DistTOT	Total distance	Km
Age	age	number
Dbh	dbh	Cm
Species_cd	species	/
Emissions	Emissions	kg/h

7.8 References

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8 Conclusions

As the sustainability of forest operations has become increasingly important in recent decades, the effective impact of forest operation in a wide context remains unclear. While the environmental aspect seems to be a key factor, sustainable forest operations are characterized by four other key performances: ergonomics, economics, quality and optimization of products and production and people and society (Marchi et al., 2018). Therefore, case-to-case solutions must be found based on site and task-specific information considering all the key performance and interaction between them.

Ensuring safety of forest operators remain a crucial aspect, especially in the context of forest operations under climate change scenarios, as discussed in Paper I, new technology for specialized ground-based harvesting machines is available and offer the possibility to expand ground-based harvesting in steep terrain (Paper II). One way to approach safety problems is to keep forest operators as far as possible from the trees and ground. Although expanding ground-based harvesting system into steep terrain could partially solve this problem, in mountains areas and in salvage logging operation, chainsaw operators are needed to perform the partial felling (cutting the stump from the windthrowed trees) when the machine is not able to reach the base of the tree (Paper III). In addition, the use of specialized ground-based harvesting systems instead of cable-based harvesting systems can lead to higher environmental impact (e.g., soil compaction)(Cambi et al., 2015).

The increase of natural disturbances will lead to an increase in low-quality wood. One of the possible solutions is to use low-quality wood for wood-chips production. The increase of new emerging markets, such as chemical and textile sectors, could lead to sustainable use low quality wood in more long-term use than wood biomass. The accessibility to these areas needs to be evaluated in advance, considering the increase of carbon emissions due to wood chipping and transportation activity (Paper V).

The environment variables are one of the limits of ground-based harvesting systems especially roughness terrain, soil bearing capacity and sensitive areas. In those areas, cable-based harvesting system and the availability of new technologies needs to be considered. New propulsion system (e.g., hybrid system) is available and can be used to reduce environmental impact (e.g., soil compaction, noise), save energy and costs and reduce the emissions of forest operation (Paper IV). As for ground-based harvesting systems, training activities need to be carried out to improve technical knowledge of forest operators and optimize the use of new technologies. While, on the one hand, new technology needs to be well-known by forest operations, the availability of the forestry

4.0 data will also increase the possibility for technician forest managers to set up better and optimize forest operations activity and chain. As proposed in Paper VI, commercial platform available via owner website leads to the possibility of monitoring machines. While this is a greater possibility for forest owners and managers, every brand of machine or equipment manufacturer gives the possibility to use their own web platform (harvester, forwarder, winch, loader, chainsaw), creating great confusion and difficulties in learning different platforms and visual interface.

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