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CO_2 emissions control in forest operations “Controllo delle emissioni di CO_2 nelle operazioni forestali”

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Summary

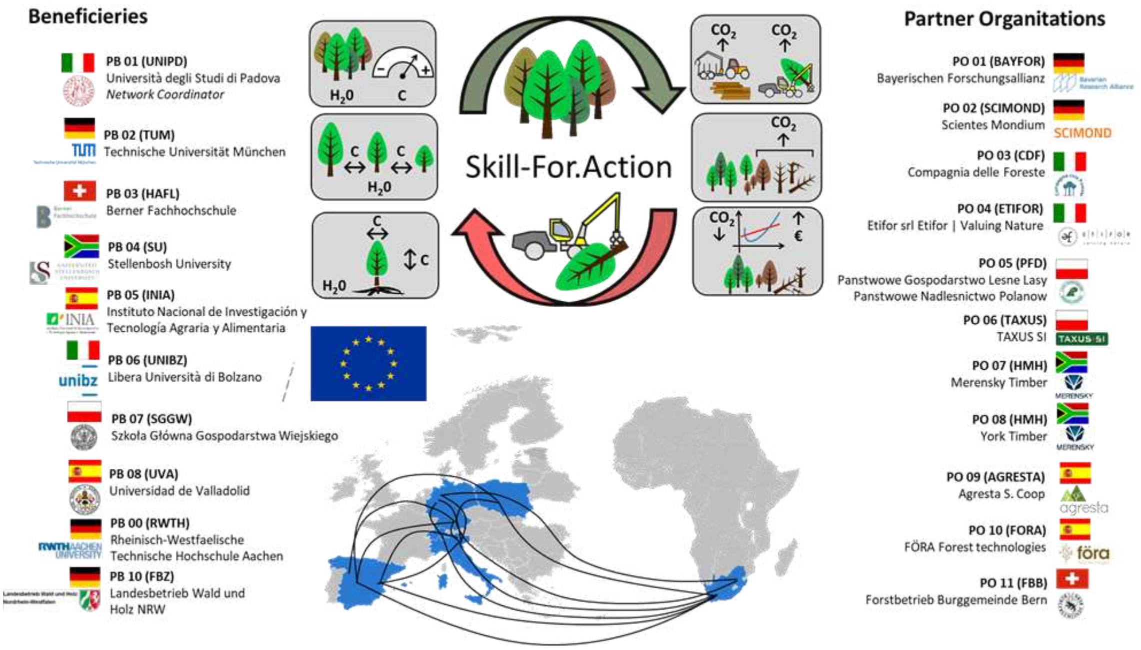
Assessing CO_2 emissions from forest harvesting operations is essential, especially as new machinery and innovative drive technologies are developed. While emissions from timber harvesting are relatively low in a global context, increasing mechanization could lead to higher emissions. Also factors such as stand conditions, terrain characteristics, wood species and operator performance can influence the emissions rate.

A thorough assessment should start with an analysis of fuel consumption per unit of product (e.g. l m-3 or l t-1), as this is fundamental in determining the level of CO_2 emissions. Indeed, carbon dioxide equivalent emissions (kg CO_2 eq) can be determined by applying an emission factor of 2.61 to each liter of fuel.

Given the EU's target to reduce greenhouse gas emissions by 40% by 2030, improving machine efficiency and introducing cleaner drive systems are key to achieving low-carbon forestry.

This thesis is developed in the frame of the topic of the ESR07 (Early-Stage Researcher) within the ETN Skill-For.Action project founded by the European Union’s Horizon 2020 research and innovation program.

The ETN Skill-For.Action project aims are to contribute and to enhance the better adaptation of forest ecosystems to climate change across Europe through creating novel and specific knowledge about improvement of carbon sink and optimizing its sources, as well as capacity building by integrating fundamental research aspects of forest ecology, modeling and applied science of forest engineering as well as risk management under uncertain future in terms of natural hazards.



Within this context, in the present thesis, new technologies and methods (such as Automatic Time Study, Can- BUS communication system, Big Data approach, etc.) were combined and tested, in order to develop a strong standard protocol for precise fuel consumption measuring in forest operations. The results obtained, show that the Automatic Work Element Detection (AWED) protocol developed, and its variations, allows not only for a precise fuel measuring and CO_2 emissions estimation. Moreover, it has a great potential, as proved in the different real case scenarios carried out during this research. Combining this protocol with in-field observations and auxiliar technologies, it was possible to develop precise productivity and fuel efficiency models, focused on different fully or semi-mechanized systems, their own different configurations, as well as on the site and stand characteristics.

Riassunto

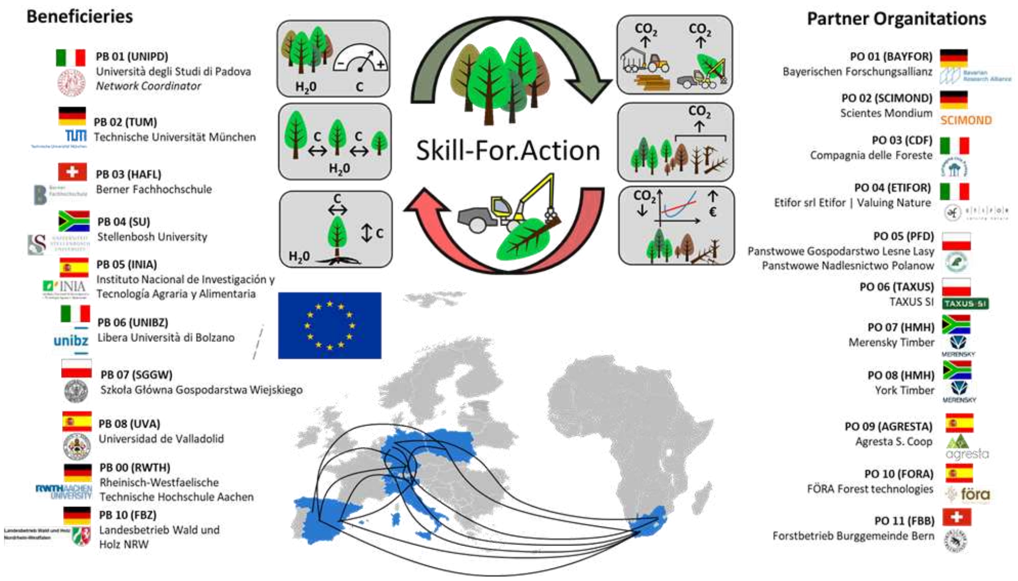
Valutare le emissioni di CO_2 derivanti dalle utilizzazioni forestali è essenziale, soprattutto con lo sviluppo di nuovi macchinari e di tecnologie di guida innovative. Sebbene le emissioni derivanti dalle utilizzazioni forestali siano relativamente basse in un contesto globale, l'aumento della meccanizzazione potrebbe portare a emissioni più elevate. Anche fattori come le condizioni del popolamento, le caratteristiche del terreno, le specie legnose e le prestazioni dell'operatore possono influenzare il tasso di emissioni.

Una valutazione approfondita dovrebbe iniziare con un'analisi del consumo di carburante per unità di prodotto (ad esempio, Lm^{-3} o Lt^{-1}), in quanto è fondamentale per determinare il livello di emissioni di CO_2. Infatti, le emissioni di anidride carbonica equivalente (kg CO_2 eq) possono essere determinate applicando un fattore di emissione di 2,61 a ogni litro di carburante.

Considerato l'obiettivo dell'UE di ridurre le emissioni di gas serra del 40% entro il 2030, il miglioramento dell'efficienza delle macchine e l'introduzione di sistemi di trazione più puliti sono fondamentali per ottenere una silvicoltura a basse emissioni di carbonio.

Questa tesi è stata sviluppata nell'ambito del tema dell'ESR07 (Early-Stage Researcher) all'interno del progetto ETN Skill-For.Action fondato dal programma di ricerca e innovazione Horizon 2020 dell'Unione Europea.

Gli obiettivi del progetto ETN Skill-For.Action sono quelli di contribuire e migliorare l'adattamento degli ecosistemi forestali ai cambiamenti climatici in tutta Europa attraverso la creazione di conoscenze nuove e specifiche sul miglioramento del pozzo di carbonio e l'ottimizzazione delle sue fonti, nonché lo sviluppo di capacità integrando aspetti di ricerca fondamentale dell'ecologia forestale, la modellazione e la scienza applicata dell'ingegneria forestale, nonché la gestione del rischio in un futuro incerto in termini di rischi naturali.



In questo contesto, nella presente tesi, sono state combinate e testate nuove tecnologie e metodi (come lo Studio Automatico dei Tempi, il sistema di comunicazione Can-Bus, l'approccio Big Data, ecc.), al fine di sviluppare un solido protocollo standard per la misurazione precisa del consumo di carburante nelle operazioni forestali. I risultati ottenuti dimostrano che il protocollo Automatic Work Element Detection (AWED) sviluppato, e le sue variazioni, non solo consentono una misurazione precisa del carburante e una stima delle emissioni di CO2. Inoltre, ha un grande potenziale, come dimostrato nei diversi scenari reali realizzati nel corso di questa ricerca. Combinando questo protocollo con le osservazioni sul campo e le tecnologie ausiliarie, è stato possibile sviluppare modelli precisi di produttività e di efficienza del carburante, incentrati sui diversi sistemi completamente o semi-meccanizzati, sulle loro diverse configurazioni e sulle caratteristiche del sito e dello stand.

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1. Introduction.

1.1. Climate Change and Forest Operations

In the actual context of a worldwide increasing human population and development, natural resources and its availability in the long-term period is essential, especially considering that its own nature is limited. Thus, its exploitation must be carried on achieving more sustainable and efficient ways of development [1]. Moreover, the effects of the Climate Change jeopardize the availability of those resources, causing an even more challenging scenario for a sustainable development. Climate Change and forest ecosystems form a sensitive dynamic relationship easily susceptible to disruptions, that can lead to sever changes with negative overall consequences for the society. When properly managed, forest ecosystems provide multiple benefits that can be classified in four main categories [2]:

- Provisioning services: fresh water and air, wood material and its derivates, wild berries, mushrooms and bushmeat, as well as cork, latex, resin, etc.
- Regulating services: climate regulation, carbon sequestration, erosion and natural hazard regulation, air pollution control and water purification.
- Cultural services: recreation, tourism, aesthetic and inspirational values, spiritual heritage and education.
- Supporting services: primary production, provision of habitats, soil formation, nutrients and water cycling.

At European level forest ecosystems span over 200 million ha, covering more than a third of its surface [3]. Nevertheless, extreme events such as windthrows, wildfires, insect outbreaks (especially spruce bark beetle, *Ips typographus*) disrupt and abruptly modify the natural dynamic of forest by killing trees, altering the functioning of the ecosystem, and affecting resource availability and the abiotic environment [4]. Between 1950 and 2020 these extreme events caused each year on average losses of 43.8 million cubic meters. However, further analysis observed that timber losses increased by 845 000 cubic meters every year, and in the las 20 years the total amount of timber damaged on average per year reached 78.5 million cubic meters, representing 16% of the annual mean harvested timber [5]. Windthrows has the higher impact on European forests, accounting for 46% of the damaged timber volume, followed by wildfires which represents 24% of the damaged timber, bark beetles representing 17% and other biotic and abiotic disturbances affecting 13% of the damaged timber volume [6].

Within this context Forest Operations (FO) represent an essential management tool, both to ensure sustainable timber supply, as well as to recover the economically lost value of the timber affected by extremes events and to prevent further risks as wildfires and insect outbreaks, which probability and severity increases after a significant natural disturbance.

In order to reduce the frequency and severity of these disruptions, as well as to ensure a sustainable development of the human society, environmental protection policies worldwide were being developed and implemented. The 2030 Agenda for Sustainable

Development and its Sustainable Development Targets (SDGs), established by the United Nation in 2015, is a clear example of the relevance of this topic. Regarding the SDGs targets, this research aims to improve the knowledge related to Goal 12, Goal 13, and Goal 15. In particular, related to target 12.2 by 2030, achieve the sustainable management and efficient use of natural resources and 15.2 by 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally and the respective indicator 15.2.1 Progress towards sustainable forest management.

1.2. Harvesting Systems in Forest Operations.

When referring to FO two main approaches can be found depending on whether all the harvesting operations are ground-based (ground-based approach) or if some of them involve the use of cables or aerial means (overhead approach). These approaches can in turn also be classified into different harvesting methods, which comprehend nowadays two main categories, Full-Tree method (FT) and Cut-To-Length method (CTL), differentiating one form the other by the product delivered at the landing point or roadside[7]. In both cases, the felling operation takes place inside the forest, and it can be done mechanically through the use of a harvester or a feller-buncher, or manually by a chainsaw operator. However, in the case of the FT method the hole tree stem (with or without branches) is transported at the landing point by a forwarder, a skidder or a cable yarder (and in extreme cases by helicopter), where the bucking operation is carried out by a processor. In the case of the CTL method, all processing operations (delimbing, topping and crosscutting the stem into different logs) take place at the stump and is usually done by a harvester. Then the already processed logs are transported to the roadside usually by a forwarder, and staked ready for the on-road transportation. Harvesting system, on the other hand, refers to all the tools and equipment combinations used to harvest the trees inside the forest and transport the timber until the roadside [7], [8]. Depending on the degree of mechanization achieved within these systems, a further distinction can be made between fully mechanized systems, partly mechanized systems and non-mechanized system. The choice between the different harvesting systems depends mostly on the terrain slope, extraction distance and ground bearing capacity. A general framework that includes all the above-mentioned classifications can be found in Figure 1.1, nevertheless it includes only the most widespread harvesting approaches, methods and systems without considering minor or less used ones.

Analyzing the worldwide trend among the different harvesting systems, it can be observed how the tendency goes towards higher levels of mechanizations, being the most popular the fully mechanized systems followed by the semi-mechanized systems. According to [7], approximatively 70 % of all harvested roundwood volume at global level is harvested through the use of fully mechanized systems, which include the CTL (37%) and FT (33%) harvesting methods. On a smaller scale FT methods are accountable for over 70% of the roundwood volume harvested in North America, meanwhile the CTL methods is the preferred one in Europe, especially in North Europe, where the share of the total roundwood volume harvested corresponding to the CTL methods reaches 95%. Although the percentage of the volume harvested associated to the CTL methods and to fully mechanized systems decreases towards South and East Europe, where partly or semi mechanized systems, especially FT harvesting methods, account for a significant share (approximatively 40%) of the annual harvested volume.

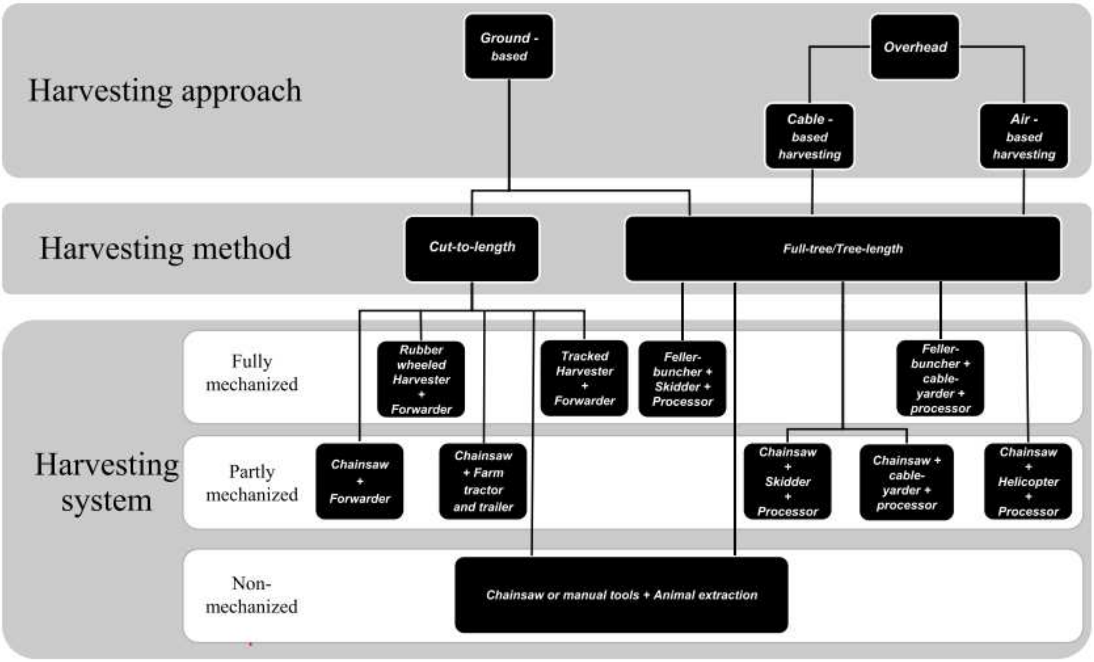


Figure 1.1. *Framework including examples of the most common harvesting operations classified according to the concepts "Harvesting approach", "Harvesting method", and "Harvesting system" (retrieved from Lundbäck, 2021).*

The tendency of the harvesting systems through higher levels of mechanization has its benefits and its drawbacks. Higher levels of mechanization usually imply bigger and heavier machines, with higher fuel consumption rates [9] and potential damage to the soil, especially in those with low bearing capacity [10]. Another drawback of the ground based fully mechanized systems is the steep terrain, however in the last years the development and implementation of cable assisted machines among other advancements, reduce this limitation. This allowed an operational range increment from a maximum 30-40% of slope (in commonly used fully mechanized systems) without cable assistance, up to 70-80% of slope when the same machines are cable assisted [11], [12]. Despite all these disadvantages, higher levels of mechanization in fully and semi-mechanized harvesting systems have supposed an overall advancement in FO. Because it not only achieves higher productivity, efficiency and makes possible a higher traceability of the timber and its chain flow, but also achieve higher operators' safety levels [13], [14], [15], [16].

1.3. Productivity and Fuel Efficiency in Forest Operations

When analyzing productivity and fuel efficiency in FO, several parameters characteristic to each operation are usually taken into account. These parameters can be classified in three main groups:

- Machine and harvesting system parameters: these parameters are strictly related to the machines in charge to perform the forest operations and their workflow. Since the operations are performed usually employing different machines types, brands, models and workflows, the availability of these parameters and their accuracy varies wildly. Some of the most relevant ones, are the extraction distance, payload, type and number of assortments, fuel consumption rate, engine revolutions per minute (rpm), speed of the machine and GPS or GNSS position.
- Site parameters: these parameters are related to the place in which the machines are operating. Their integration in datasets and in further analysis aiming to predict productivity of efficiency of FO is fundamental, to comprehend the results regarding the performance analysis of the FO as a whole. The list of these parameters can be very broad, usually including the terrain slope, the soil bearing capacity and roughness, soil water content and the type of road.
- Stand parameters: these parameters include the characteristics of the stand in which the machines carry on the FO of interest. Among them there are the stand´s tree species, age, position of the selected trees, forest structure (plantation or natural, heterogeneous or even age trees, thinning operation, final felling or salvage logging), as well as the diameter at breast high (DBH) of the selected trees for the harvesting operation, as well as, the DBH of the remain ones.

Reviewing the available bibliography, it can be observed that a great number of studies focus on productivity and efficiency models and analysis [12], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], considering different combinations of the above-described parameters and harvesting scenarios. Ultimately, there is a common consensus among all of them, considering the fuel consumption rate as the most essential parameter, together with the volume extracted and the machines productive time, to estimate operations productivity and efficiency, respectively. Moreover, considering the fuel consumption rate, indirect carbon dioxide equivalent emissions (kg of CO_2 eq) can be estimated by generally applying a conversion emission factor of 2.6-2.7 [30], [31], [32], [33]. CO_2 eq emissions control is essential to achieve lower carbon emission harvesting systems, since it is one of the main compounds of greenhouse gases (GHG) responsible for the increasing severity of the Climate Change. Additionally, achieving lower carbon emission is essential considering that in the European Union GHG emissions must be reduced by 55% by 2030 (with 1990 as base-line) [34] .

In a recent review [35] of the latest publications related to the fuel consumption and CO_2 emissions in FO published from 2014 to 2018, 61 relevant studies were found that reported fuel consumption figures for a total of 448 various forestry machines, using more than 20 different measuring units. This situation can clearly lead to difficulties when comparing values among studies, highlighting the relevance, therefore, of a standardized, comparable and reliable method for measuring fuel consumption in FO [36]. The development of a comparable and reliable methodology for the fuel consumption measurement is essential in FO sustainability, enabling the improvement of the decision-making process of the different forest stakeholders such as forest managers, contractors, machine manufacturers and policy makers. A reliable method for fuel consumption measurement is also fundamental in order to "feed" one of the most powerful and wildly utilized analysis tool for assessing the environmental sustainability of a process or a product, the Life Cycle Assessment (LCA) [37]. Nevertheless, in the above-mentioned context, of a clear standardized method missing, precise and broad datasets needed to be gathered and process through the use of Big Data approaches in order to develop accurate LCAs, becomes challenging.

With the recent technological advances affecting most of the industrial sectors, among many other aspects of nowadays human society, some interesting results are being obtained when implementing them in FO. This process had been a driving factor over the last years in the forestry sector and it is known as Precision Forestry (PF). The development of modular and cloud-connected data loggers allows the collection of a great variety of engine and machines working parameters. Through the use of the pre-developed J1939 Standard for forest machines data collection, it is possible to measure the most fundamental variables of a machine workflow in terms of its productivity and fuel efficiency. Nowadays, these innovative approaches are a fundamental part of the Industry 4.0 [38] implementation in FO. Another crucial development in FO was the implementation of the Internet of Things (IoT) concept [39] , that makes possible for each machine to send (and receive) data to a central location, from where all operations and machine can be monitorized. This management system is known as Fleet Management System (FMS) and, when implemented, allows for a full traceability of the timber and of the performed FO sustainability form cradle-to-gate.

Traditionally, fuel consumption is calculated by measuring the fuel volume when refilling or through the use of flow meters, while new technologies, especially those based on the Controller Area Network (CAN-bus) enables cheaper and easier measurements that are commonly accepted worldwide as the most accurate fuel measurement techniques [40]. Nowadays FO machines, as well as most heavy-duty, agricultural and transport vehicles, can be monitored through the use of specific Electronic Control Units (ECUs). These ECUs register all engine`s sensors readings communicating its status and working parameters to the CAN-bus, generally according to a specific standard, which in the case of FO machines is the SAE J1939. Additionally, using the CAN-bus system combined with Geographical Information Systems (GIS), forest contractors can track all vehicles from a central location through the Fleet

Management System (FMS). Moreover, in nearly all modern FO harvester and forwarder not only engine parameters can be recorded, but also other specific quantitative and qualitative parameters related to the CTL system, thought the use of the StanForD (Standard for Forest Machine Data and Communication) [41]. These parameters include among others timber volume and number of logs processed, average productive time, average fuel consumption, etc., with a daily or hourly detail level. This Standard was developed by Sweden's Skogfordk and is one of the most widely used communication systems by forest machine manufacturers, such is the case that a new release including also skidders, feller-bunchers, and log loaders, was announced to happen during 2024. However, elucidating main and interactive effects of variables and operator behavior on fuel and time consumption is still challenging. It requires more detail information regarding loads volume and characteristics, such as number and type of assortments, as well as stand conditions such as harvesting density and terrain conditions [42].

1.4. Thesis aims

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) makes possible the monitoring and evaluation of forest resources, providing a tool for forest management to ensure the traceability of forest products [38], [39] and a tool to validate theoretical models regarding forest harvesting systems productivity and fuel efficiency [43].

Operational productivity studies and classic time studies have been always a fundamental tool in FO and thus, wildly performed and standardized [44]. These standardized studies are based on systematic productivity modeling and statistical analytical procedures, that allow for a broader comparation possibility among different harvesting operations productivity.

Merging the previously mentioned technological advances within the operational productivity studies methodologies, it could be possible to also study the sustainability of different harvesting systems through fuel efficiency and CO_2 emissions models. Nevertheless, the fully automatization of FO and its monitoring is still in its first stages of development, existing a considerable gap of knowledge and possibility for further development and improvements.

Within this context the general aim of this thesis is to develop a robust standardized protocol for micro-metering fuel consumption in FO, that will provide the necessary data to create more comparable fuel consumption and CO_2 emission models in fully and semi mechanize harvesting systems. This thesis is presented as a collection of three different scientifical publications, each of them approaching different specific objectives of the thesis:

- First publication: aims to evaluate the benefits of automatic data collection via FMS and to assess machine productivity, fuel consumption, CO_2 emissions, and engine parameters using Big Data approaches with GIS and R software [45].

- Second publication: aims to test the Automated Time Study (ATS) methodology in a semi mechanized system, without StanForD in varied mountainous terrains, for fuel consumption and production models development.

- Third publication: aims to utilize Automatic Work-Element Detection (AWED) for precise data collection in order to analyze the main factors influencing forwarder productivity and fuel efficiency, such as slope, speed, distance, payload and assortment type.

1.5. List of publications

The publications title, authors and status are as follow:

- First publication:

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(24), 16751. https://doi.org/10.3390/su142416751

Data are available through the following repository link:
http://researchdata.cab.unipd.it/id/eprint/659

- Second publication:

[In peer review process] **Bacescu, N. M.**, Cadei, A., Moskalik, T., Wiśniewski, M., Talbot, B., & Grigolato, S. *Modelling skidding extraction in mountainous forest though engine data acquisition and analysis.* Submitted to European Journal of Forest Research Pre-Print https://doi.org/10.21203/rs.3.rs-4613216/v1 This work is licensed under a CC BY 4.0 License

Data are available through the following repository link:
https://researchdata.cab.unipd.it/id/eprint/1378

- Third publication:

[Accepted] **Bacescu, N. M.**, Marchi L., Hueller S. & Grigolato, S. *Evaluating variables' influence on forwarder performance and fuel-efficiency in mountain salvage logging using an automatic work-element detection method.* Submitted to Forests MDPI.

Data are available through the following repository link:
http://researchdata.cab.unipd.it/id/eprint/659

**The references related to this chapter can be found at the end of this document.*

2. PAPER I: *Efficiency Assessment of Fully Mechanized Harvesting System Through the Use of Fleet Management System*

Bacescu, N. M., Cadei, A., Moskalik, T., Wiśniewski, M., Talbot, B., & Grigolato, S. (2022). Sustainability, 14(24), 16751. https://doi.org/10.3390/su142416751
Data are available through the following repository link:
http://researchdata.cab.unipd.it/id/eprint/659

2.1.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/m3 for the harvesters and 2.56 kg of CO_2 eq/m3 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

2.2.Introduction

The improvement of harvesting methodologies plays an important role in the optimization of wood production in a context of sustainable forest management [1]. 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 [2]. 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 labour. By increasing the level of mechanization for the development of the activities instead of manual labour, not only higher productivity but also greater operator safety is achieved [3]. 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 [4].

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 labour, 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 [5]. 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 [6,7].

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 [8]. 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 [9].

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 [10,11] and a tool to validate theoretical models regarding forest harvesting systems and efficiency [12]. 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 [13], 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) [14]. 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) [15,16]. 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 behaviour 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 [17]. 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 analyse 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 analysed in the contest of Scots pine forests in gentle terrain located in Poland.

2.3.Materials and Methods

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 2.1). 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.

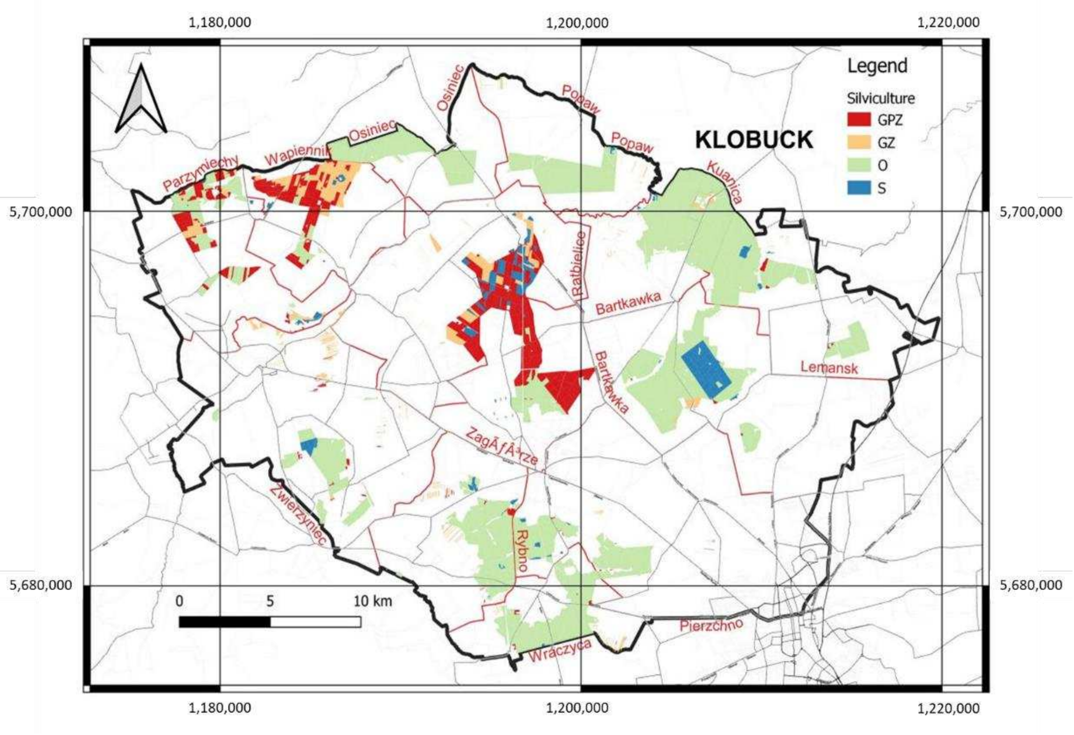


Figure 2.1. *Forest management units in the Kłobuck Forest District. GPZ—selection/clear cutting; GZ—clear cutting; O—multifunctional protective forests, S—special (protected) forests.*

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 stand 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-levelling cabin: One (H1) was equipped with the H414 harvesting head, and the other (H2) was equipped with the H480C Harvesting Head (Table 2.1). 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-levelling cabin (Table 2.2). 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 2.1. *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	7 927	
Width	mm	2 960	
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 2.2. *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	1 735	1 630

* at 1900 rpm.

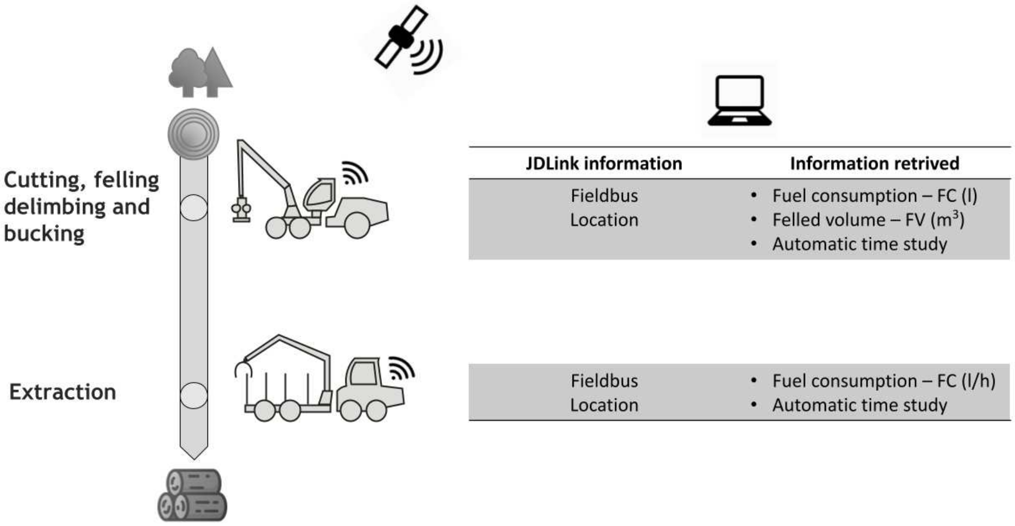
Data Collection

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 analyse and understand the performance of the machines in terms of efficiency, work activity was divided into different work elements (Table 3.3).

Table 2.3 *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 2.2).



JDLink information	Information retrived
Fieldbus Location	• Fuel consumption – FC (l) • Felled volume – FV (m³) • Automatic time study
Fieldbus Location	• Fuel consumption – FC (l/h) • Automatic time study

Figure 2.2. *Schematic visualization of the wood procurement system JDlink™.*

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) [18]. 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.

2.4.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 [19,20]. 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 analysed 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 analysed. As a result, a database that could be characterized as big data was obtained.

To analyse 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 analyse 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 [21]. Carbon dioxide equivalent emissions (kg CO_2 eq) were calculated applying an emission factor of 2.61 to each liter of fuel consumed [22].

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 [23] and to differentiate the fuel consumption variation among the different activities performed.

2.5.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. Analysing 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.

Harvesters' Analysis

The descriptive statistics of the work element of the harvesters are shown in Tables 2.4 and 2.5. 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 2.4 *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 2.5. 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 2.5. *Fuel consumption and CO_2 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	203	7303.98	42.21	18.39	1.51	47.66	15.43	40.27
H1	Process		8827.63	51.01	19.78	1.3	51.34		
H1	Other		1173.11	6.78	4.22	1.26	4.25		
H2	Preparation	230	7951.52	43.63	17.84	1.6	46.35	16.16	42.17
H2	Process		9138.12	50.15	20.57	1.43	53.27		
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 2.6 and 2.7.

Table 2.6. *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 2.7. *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

Forwarders' Analysis

The descriptive statistic regarding the time consumption of the work element of the forwarders is shown in Table 2.8. 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, analysing the non-parametric tests performed (Tables 2.9, 2.10 and 2.10, 2.11), 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 2.8. *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 2.11. 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 2.9 and 2.10) 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 2.9 *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 2.10 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 2.11 *Fuel consumption and CO_2 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		

2.6.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 analysed 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 [23]. It is interesting to note that, in a different study where the productivity of the CTL system was analysed in aged oak coppice stands [24], 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). Analysing 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 m3/h) was lower than the productivity of H1 (26.63 m3/h) and the fuel consumption, per product unit, was higher in the case of the H2 (0.72 L/m3) than in the case of H1 (0.57 L/m3). 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 [25,26], 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 [27-29]. 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 [19,20]. 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.

2.7.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 analyse 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.

2.8.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	$130 \le P \le 560$	2011.01	3.5	0.19	-	2	0.025
M	$75 \le P < 130$	2012.01	5	0.19	-	3.3	0.025
N	$56 \le P < 75$	2012.01	5	0.19	-	3.3	0.025
P	$37 \le P < 56$	2013.01	5	-	4.7	-	0.025

Stage IV

Cat.	Net Power	Date	CO	HC	NOx	PM
	kW		g/kWh			
Q	$130 \le P \le 560$	2014.01	3.5	0.19	0.4	0.025
R	$56 \le P < 130$	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	$8 \le P < 19$	2019	6.6	7.50 [a,c]		0.4	-
NRE-v/c-3	CI	$19 \le P < 37$	2019	5	4.70 [a,c]		0.015	1×10^{12}
NRE-v/c-4	CI	$37 \le P < 56$	2019	5	4.70 [a,c]		0.015	1×10^{12}
NRE-v/c-5	All	$56 \le P < 130$	2020	5	0.19 [c]	0.4	0.015	1×10^{12}
NRE-v/c-6	All	$130 \le P \le 560$	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.

2.9.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

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3. PAPER II: *Modelling skidding extraction in mountainous forest though engine data acquisition and analysis*

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https://doi.org/10.21203/rs.3.rs-4613216/v1 This work is licensed under a CC BY 4.0 License
Data are available through the following repository link:
https://researchdata.cab.unipd.it/id/eprint/1378

3.1. Abstract

This study investigates the feasibility of using standardized SAE J1939 data from forestry machines, specifically focusing on a clam-bunk skidder, to enhance the decision-making process and ensure the sustainability of forest operations in the context of Climate Change. The study was conducted between January and September 2023, across three sites in northeast Italy. The main objectives were to identify work phases, determine their durations, calculate fuel consumption, and create models for production and fuel consumption per work cycle, considering extraction distance and terrain slope. The feasibility of the Automated Time Study (ATS) methodology was tested for the first time in a mountainous region with varying slopes and stand compositions. Results showed that over 82% of working cycles were successfully identified, with 60-70% accuracy in identifying work elements within cycles. This high identification rate allows machine operators to detect bottlenecks and improve efficiency, additionally, this methodology aims to predicting future operational impacts and costs based on statistical analysis implemented by using a Big Data approach. However, the ATS methodology has limitations, potentially leading to significant estimation errors, thus critical thinking and effective communication with machine operators are essential to obtain accurate data. The study suggests further research to enhance accuracy, possibly incorporating Machine Learning or Artificial Intelligence to better detect work cycles and non-standard activities.

Keywords: cut-to-length, big data, productivity, fuel efficiency, mountain forest

3.2. Introduction

The implementation of climate-smart forestry [1] underscores the importance of a careful selection of forest management criteria and strategies. This approach, tailored to the specific characteristics of the site, takes into consideration the impacts of climate change, associated risks, and the ongoing evolution of the forest ecosystem [2]. As a consequence, the application of a climate-smart forestry approach requires efficient forest harvesting systems optimizing the socio-economic-environmental criteria [3].

Harvesting systems optimizing socio-economic-environmental criteria can nowadays capitalize on the extensive data acquisition [4] by specialized forest machinery and, consequently, on data processing aimed at understanding machine interactions with the operating environment [5]. The ability to acquire substantial amounts of data and subsequently process it is feasible within the context of specialized machinery equipped with advanced control and diagnostic systems.

The use of specific communication protocols plays a crucial role in ensuring effective interoperability. A notable example is the SAE J1939 protocol [6], commonly employed in heavy-duty vehicles.

This standard uniformly defines the formats of various parameters, allowing for standardization in managing key components of the machines, such as engine control, transmission, braking systems, and the articulated crane used for timber handling or for the timber processing head. Thanks to this regulation, communication between different control systems occurs in a structured manner, facilitating monitoring, diagnosis, and control of specific operations, thereby contributing to ensuring the efficient and safe operation of specialized machinery.

In the frame of fully-mechanized Cut-To-Length (CTL) systems, harvester and forwarder data are successfully fully exploited in order to optimize the productivity and efficiency of the machine [7], [8], [9], as well as to reduce the impacts on the environment [10], [11], [12], [13], [14] and to increase machine autonomy in order to facilitate machines operators work and safety [15]. However, despite the fact that in the European Union alone, purpose-built skidders or tractor-derived skidders extract at least 40% of the annual cut, which means over 100 million cubic meters per year [16], [17], very few to no studies [18], [19] have been carried out on exploiting the use of standardized SAE J1939 data. Defining skidders performance in terms of eco-efficiency and thus in term of fuel-consumption and the indirect CO_2 emission rate will help to cover the existing gap in knowledge regarding the monitoring of Cut-To-Length (CTL) or Full-Tree (FT) harvesting operations. Nevertheless, in industrialized and productivity focused cases, such as plantations or productivity aimed forests worldwide, the benefits of exploiting this technology are rising interest, being able to fill the gap of knowledge regarding similar but also different extraction systems than the usually used ones in Europe[20], [21], [22]. Moreover, with the new technological advancements such as Industry 4.0, Precision Forestry (PF) and the integration of Big Data tools into the data gathering and analysis, it is possible to access productivity and performance figures, similar to the most advanced systems, also in the case of this machines (skidders, feller bunchers, log loader, etc.).

The aim of this paper is to assess the feasibility of utilizing standardized SAE J1939 data obtained from a clam-bunk skidder in Full-Tree extraction system in mountain forest for the following purposes: 1) identifying the work phases, 2) determining the time duration of each work phase to calculate the total working time for work cycle, 3) establishing the fuel consumption for each work phase and the total fuel consumption for work cycle, and ultimately, creating a production model and a fuel consumption model per work cycle in relation to extraction distance and terrain slope.

3.3. Materials and Methods

Case Studies

The study was carried on from January 2023 until September 2023, during which period, machine performance data was collected including three working sites located in between Veneto Region and Friuli-Venezia Giulia Autonomous Region in the northeast Italy (Figure 3.1 and Table 3.1).

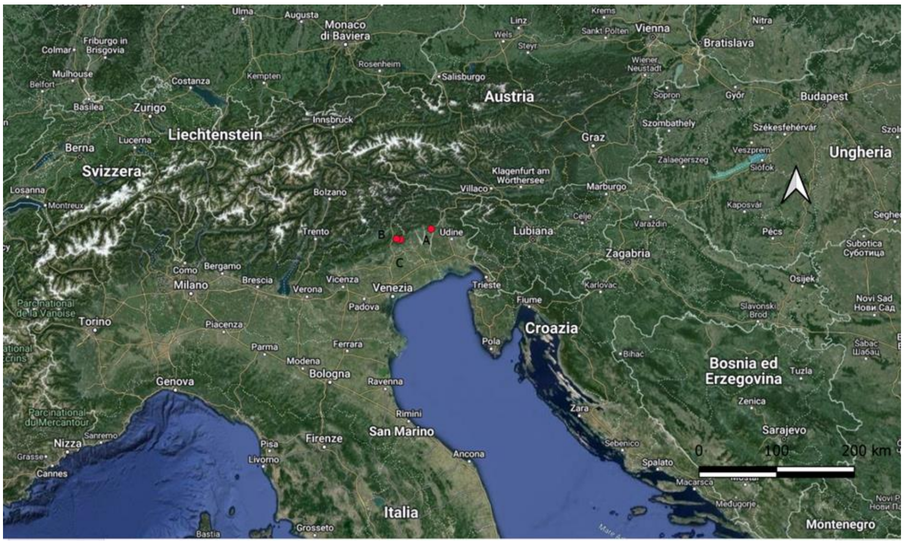

Figure 3.1. *Location of the study working sites.*

Table 3.1. *Stand description and characteristics of the three different working sites.*

	Site A	Site B	Site C
Location	Fregona	Pian del Cansiglio	Pian del Cansiglio
Province	Treviso	Belluno	Pordenone
UTM (x; y) Coordinates	(339 313; 5 115 720)	(297 353; 5 105 009)	(302 245; 5 103 889)
Elevation (m a.s.l.)	246	1 396	1 354
Average Slope (%)	1.4	15.3	10.7
Species (% of volume)			
Picea abies	-	-	5
Fagus sylvatica	-	100	95
Robinia pseudoacacia	95	-	-
Pseudotsuga menziesii	5	-	-
Extracted volume (m^3)			
Picea abies	-	-	62
Fagus sylvatica	-	3 018	1 378
Robinia pseudoacacia	1 000	-	-
Pseudotsuga menziesii	52	-	-

Site A involved a private property located in Pordenone province (Friuli-Venezia Giulia Autonomous Region) at 246 m a.s.l. where the main specie was Black Locust (*Robinia pseudoacacia* L., 1753), with sporadic (less than 5 %) Douglas fir (*Pseudotsuga menziesii*) presence. The final end-use of the extracted material was intended for biomass (chips) and firewood for heating purposes.

Site B and C were both two contracts of the same batch located in a public owned forest (Foresta del Cansiglio) in Veneto Region and Friuli-Venezia Giulia Autonomous Region, respectively. Located at an average altitude of 1 375 m a.s.l., site B had a mixed irregular stand composition formed by beech (*Fagus sylvatica L.*), spruce (*Picea abies L.* H. Karst.) and silver fir (*Abies alba* Mill.), from which were extracted about 3 018 m^3 of beech. From the total mass extracted, about 336 m^3 were classified as industrial roundwood category, as for the remaining 2 682 m^3 extracted were classified as biomass (wood chips) and firewood. The total volume per hectare ranged between 500-600 m^3.

Finally, regarding site C located at an average altitude of 1 354 m a.s.l., the stand composition was formed by beech (*Fagus sylvatica* L.) and spruce (*Picea abies L.* H. Karst.), from which were extracted 1 378 m^3 of beech from a total of 1 575 m^3, and 62 m^3 of spruce from a total of 77 m^3. The total mass per hectare was composed by 3.6 m^3 of spruce and 73.28 m^3 of beech. All the material extracted was classified as biomass (wood chips) and firewood.

Machine Description

The machine studied is the Equus 175 N skidder (Figure 3.2), a vehicle of medium size and capacity compared to other competitors on the market, designed to work in a variety of slope and ground conditions, fitting to the needs of small companies operating mainly in mountainous areas. The skidder Equus 175 N version was equipped with a hydraulic boom, clambunk and two winches.

The Equus 175 N skidder is fitted with a Cummins B 4.5 Litres diesel engine with an Electronic Common Rail direct fuel injection system, developing 175 hp and a maximum power of 129 kW at 2 200 rpm with a torque of 780 N/m at 1 500 rpm. This engine is in the EU Stage V emission class. The power developed by this 4-cylinder engine and drive chain makes it possible to reach speeds of up to 40 km/h when travelling on roadways. The undercarriage of the tractor consists of two frames, commonly known as an articulated machine, that allows independent movement of the two sections on both the horizontal and vertical axes. Mounted on the front frame of the machine is the driver's cabin, the engine, the hydraulic pump controlling the brakes and frame steering, the hydraulic main traction system connected to the transmission gears, and the hydraulic adjustment elements. A hydraulically operated blade is also mounted to push logs / brush and for light bulldozing where needed for driving (e.g. onto or off a road, moving a boulder etc.). In the rear frame, on the other hand, a double-drum winch is located with a towing capacity of up to 15 tones and a maximum winching distance of 160 meters, as well as, the Equus HR 120/75 hydraulic swivel arm with a moment of 120 kN/m and a reaching range of 7.5 meters, and the clam-bunk grapple.

Compared to other skidders on the current market (Figure 3.3), the Equus 175 N has medium to high power characteristics compared to those produced in Europe, e.g. by Hittner or Irum. When compared to non-European manufacturers such as Tigercat or John Deere, the machine ranks among the smallest in terms of power. However, it can be seen that models of equal performance such as the Tigercat 602 (129 kW) and HSM 805 (129 kW) weigh 6.3 and 3.34 t more respectively, while models of similar weight such as the HSM 805S and Irum 690 S5 have 25 and 29 kW less power, respectively.

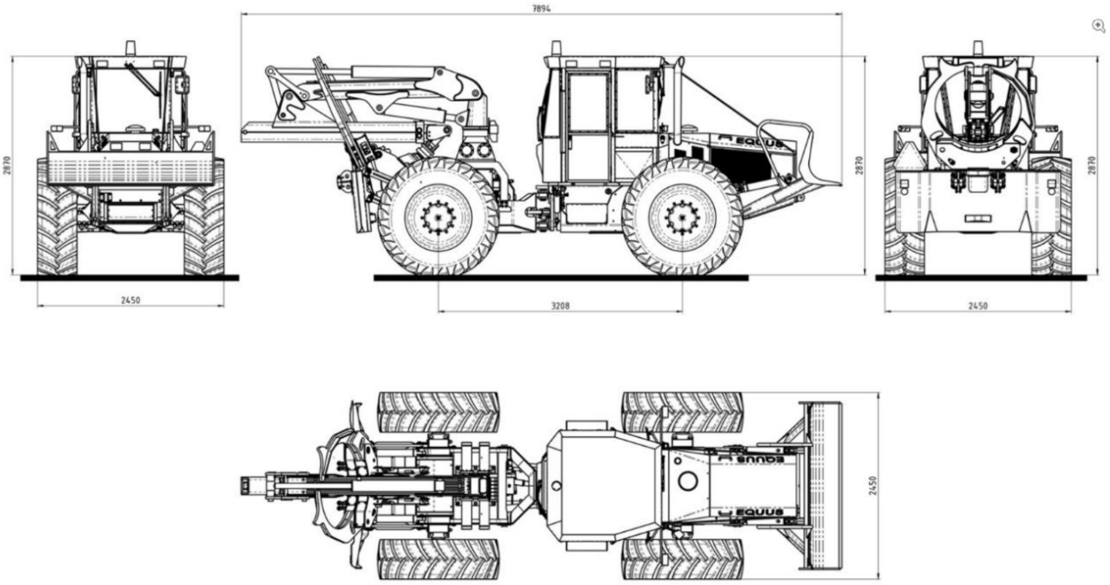

Figure 3.2. *Equus 175 N skidder configuration and measurements [mm].*

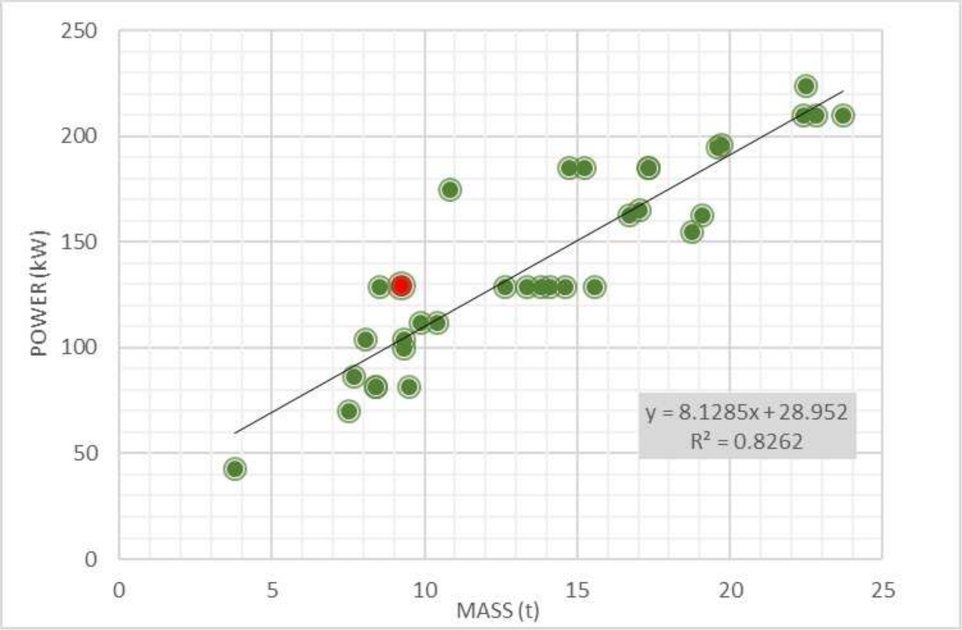

Figure 3.3. *Mass (t)/Power (kW) ratio comparison of the current skidders on the market. The machine model under consideration is represented by the red dot.*

Data Collection

The data collection was carried out between January and August of 2023, during which period a CAN-bus data logger was connected to the OBC plug of the machine in order to record and store all available engine working parameters under the SAE J1939 standard. The data logger used in this study was the CANedge2 manufactured by CSS Electronics [23]. The CANedge2 enables stand-alone logging of the data from the CAN-bus of the machine to an SD memory card, and offers a range of configuration options such as message filtering, pre-scaling, transmit messages, cyclic logging, among others. Another advantage driven from the use of this technology is that is a modular data logger, meaning that is possible to connect different extension modules (sensors) to the main unit. In this study a CANmode.gps extension module was used in order to capture the position information of the machine while working. The CANmod.gps is a combined Global Navigation Satellite System (GNSS) and 3D Inertial Measurement Unit (IMU) sensor module, and it records the best possible positioning information by combining a variety of GNSS signals (GPS, GLONASS, Galileo, BeiDou).

A manual time study was performed during one fully operational day of the machine. During the time study, all working cycles and working elements within each working cycle were recorded (Table 3.2). In the time study, all machine nonproductive times, including nonproductive periods over thirty seconds, were recorded. As a result, a total of seventeen (17) working cycles were identified during the manual time study. Also, based on the field observations (average volume extracted per cycle) and on the few studies carried out [24], [25]regarding the influence of the load volume, an average load of 3 cubic meters per cycle was assumed.

Table 3.2. *Work elements recorded while performing the manual time study.*

Element	Description
Traveling Unloaded	Begins when the machine starts to move to a new position from the landing area and ends when the boom starts to swing towards the first log/stem to be extracted.
Loading	Begins when the machine stops driving empty and the boom starts to swing towards a log/stem to be extracted or the skidding cable drums starts to spin releasing the cable, and ends with the boom resting in its original position after the log/stem was positioned and secured by the clambunk.
Traveling while Loading	Begins when the boom is resting in its original position after the log/stem was positioned and secured by the clambunk. and ends when the boom starts again to swing towards a log/stem to be extracted and ends with the boom resting in its original position after the log/stem was positioned and secured by the clambunk.
Traveling Loaded	Begins when the boom is resting in its original position after the log/stem was positioned and secured by the clambunk and ends when the machine arrives at the landing area and the boom starts to swing, in order to download the logs/stems.
Unloading	Begins when boom starts to swing, in order to unload the logs/stems and ends when the boom rest in its original position and the machine starts to move again.
Delays	Clearing ground; moving tops, branches and slash; stacking logs; refuel time (in shift); repair time (in shift); maintenance time (in shift); other delays (planning, rest…)

3.4.Data Analysis

Due to poor weather conditions and the reduced experience of the machine operator on this specific machine (less than one year of experience), the total number of days in which the machine was working and data was recorded by the Can-Bus data logger was ninety-nine (99) in total. From the total number of days recorded, a first filter was applied, eliminating those days in which GPS drift effect occurred, due to poor GPS signal received, making an accurate positioning of the machine impossible.

Within the working days remaining, a second filter was applied, in this case the filter consisted on a code developed using Rstudio [26] and QGIS 3.18.0 Zurich [27] software, which allows to identify and isolate each working cycle performed by the machine, as well as, each working element inside each working cycle, based on the GNSS position of the machine, and on the machine's engine parameters (Table 3.3). In order to test the suitability of this methodology, the duration of each working cycle and work element identified during the manual time study carried out was compared to the duration of the work cycles and work elements identified through the implementation of this automatic time study.

Moreover, the implementation of this methodology enables the elimination of all non-productive periods, which might have occurred, and allows an accurate estimation of time usage and fuel consumed daily, hourly, per working cycle or even by working element, carried out by the machine at any time.

Table 3.3. *Parameters considered in this study, recorded with a frequency of 1 second.*

Machine Parameters	**Format/Units**
Date	dd/mm/yyyy
Hour	hh:mm:ss
Engine speed	rpm
Altitude	m a.s.l.
Actual engine torque	%
Distance trip	m
Engine fuel rate	l/h
Latitude	°N
Longitude	°E
Engine-based machine speed (based on rpm and shifts ratios)	m/s
ABS (Anti-lock Braking System) wheel sensor-based machine speed	m/s
Additional Parameters	Units
Slope	%

Additionally, at cycle level, time and fuel efficiency were modelled (Table 3.4), considering from all the available variables the average slope and extraction distance per cycle, as the most significant explanatory variables [12], [28], [29]. Also, time and fuel efficiency were modelled considering the slope, distance and machine Traveling Unloaded or machine Traveling Loaded status. During this study, all machine's Traveling Loaded work phases occurred while traveling downhill, meanwhile all machine Traveling Unloaded phases occurred while traveling uphill. Regarding the site variable, it was assumed as part of the random intercept (GLM). A likelihood ratio test was used to evaluate the significance of the individual variables, assuming as significant a level of 0.05. One of the limitations of this methodology was the inability to model time and fuel consumption, during the loading and unloading phases of the working cycle, due to the fact that no machine or engine parameter were found to be a significant explanatory variable for its modelling.

Table 3.4. *Time and Fuel Efficiency models.*

Time Efficiency models	**Equations**
Generalized Lineal Model (GLM) of Time Consumption per Cycle	$T_{CYCLE} = f$ (Slope, Extraction Distance)
Generalized Lineal Model (GLM) of Time Consumption Unloaded	$T_{UNLOADED} = f$ (Slope, Traveling Unloaded Distance)
Generalized Lineal Model (GLM) of Time Consumption Loaded	$T_{LOADED} = f$ (Slope, Traveling Loaded Distance)
Fuel Efficiency models	Equations
Generalized Lineal Model of (GLM) Fuel Consumption per Cycle	$F_{CYCLE} = f$ (Slope, Extraction distance)
Generalized Lineal Model (GLM) of Fuel Consumption Unloaded	$F_{UNLOADED} = f$ (Slope, Traveling Unloaded Distance)
Generalized Lineal Model (GLM) of Fuel Consumption Loaded	$F_{LOADED} = f$ (Slope, Traveling Loaded Distance)

3.5.Results

As a result, using this Automatic Time Study methodology, a total of twenty-three (23) working days and two hundred seventy-eight (278) working cycles were successfully identified for all the working sites, distributed as shown in Table 3.5, representing approximately between 60-70% of the total number of cycles performed.

Table 3.5. *Effective working days and working cycles identified applying RStudio script.*

Site	**Work days**	**Cycles**
A	9	137
B	6	43
C	8	98

In order to validated the accuracy of the methodology applied to identify the above work days, working cycles, as well as the work elements included in each working cycle, the same filters and script that were applied to the data recorded by the data logger were applied on the same day that the manual time study was performed, making it possible to synchronize both data sets by their respective time stamps. As shown in Table 3.6, after performing the non-parametric Wilcoxon test, there were no significant differences (at a confidence interval of 95%) between the two methods. The time study based on the use of the Can-Bus data logger was designated as Automatic Time Study (ATS), while the other constituted the Manual Time Study (MTS).

Table 3.6. *Average productive and work elements time distribution in minutes, and Wilcox p-values.*

Productive average time (min)			Driving average time (min)			Loading average time (min)			Unloading average time (min)		
ATS	MTS	p-value	ATS	MTS	p-value	ATS	MTS	p-value	ATS	MTS	p-value
14.86	14.32	0.6098	11.25	10.04	0.0948	2.84	3.46	0.4909	0.78	0.82	0.1476

Descriptive statistics

Firstly, the normal distribution of the data set was tested, considering both fuel consumption (l/cycle) and time consumption (s/cycle) per working cycle as observational units.

In both cases the Shapiro-Wilk normality test shows p-values below 0.05 (at a confidence interval of 95%), more specifically a p-value of 0.0012 was obtained testing the normality considering the fuel consumption per working cycle as observational unit and a p-value of 0.0157 was obtained testing the normality considering the time consumption per working cycle as observational unit, thus based on these results, it can be concluded that the data is not normally distributed.

Secondly, the data set was divided into time (s) and fuel consumption (l) per working cycles performed on daily basis, as observed in Figures 3.4 and 3.5 respectively. Studying Figure 3.4, it can be observed, as the days pass by, that the average time usage per cycle increased, especially during the dates in which the machine was working on the site A and C (from 02/02/2023 to 14/02/2023, and from 19/06/2023 to 30/06/2023).

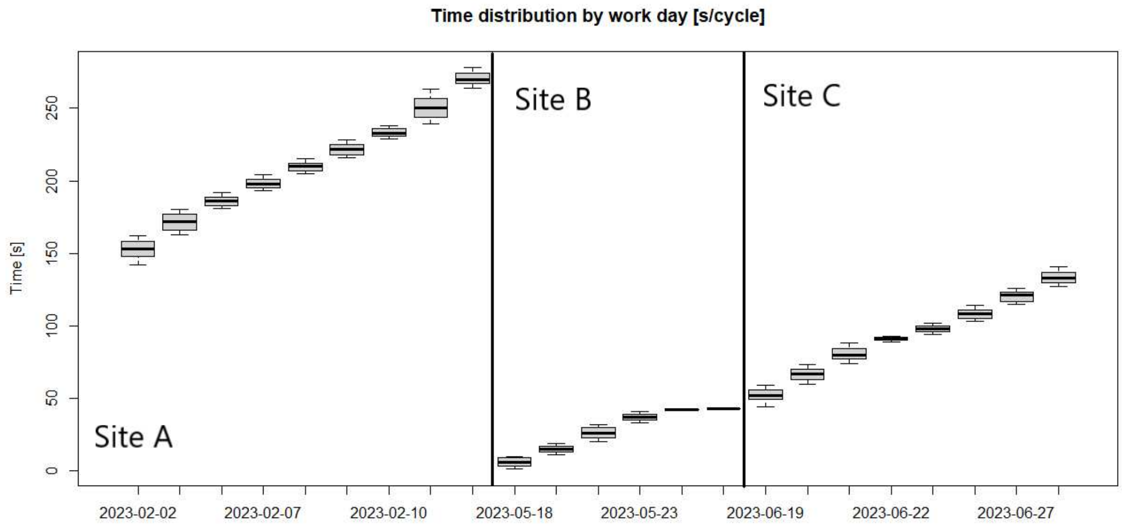

Figure 3.4. *Time consumption per working cycle (s/cycle).*

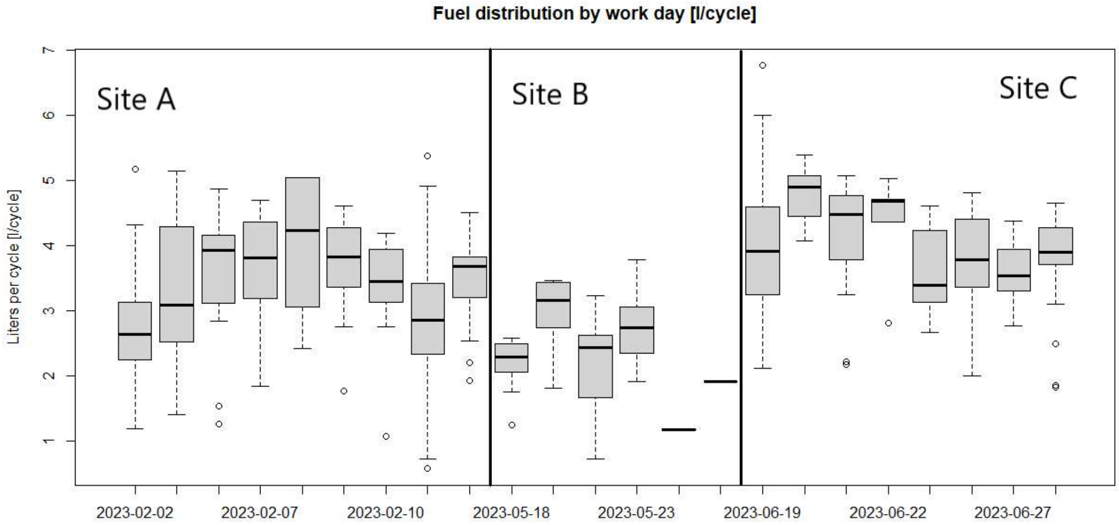

Figure 3.5. *Fuel consumption per working cycle (l/cycle).*

Regarding the fuel consumption recorded per each cycle performed on a daily basis (Figure 3.5), it does not appear to develop such a clear evolution or relationship between the measurements recorded for each cycle and the different sites (as regarding the time distribution in Figure 3.4.

Finally, as part of the descriptive statistical analysis carried on, it was also analysed the fuel and time consumption among the different work elements in which each working cycle was divided. Analysing the machine parameters was observed how some integrated sensors, or combination of them, reported different values of the same parameter aimed to be measured.

Specifically, the biggest variation was detected between the two sensors that were responsible for the machine speed measurement, machine´s ABS Wheel sensor and CAN-Bus data logger`s GNSS sensor. On one hand, machine´s ABS Wheel sensor sensitivity was higher that the Data logger´s GNSS sensor, allowing a more refined detection of the changes in the machines moving status (if the machine is moving or not), but at the same time, it overestimates the speed of the machine while moving. On the other hand, the Data logger´s GNSS sensor detects accurately the machine speed; however, its sensitivity is not so high as the ABS Wheel sensor. As a consequence, in order to identify the different work elements, two different classifications were made based on the speed measurement method (Table 3.7).

Table 3.7. *Fuel and time consumption per each work element detected.*

Speed measurement method	Work Element detected	Fuel consumption (liters)			Time consumption (minutes)		
		Mean	**Median**	**SD**	**Mean**	**Median**	**SD**
ABS Wheel sensor-based machine speed	Machine Traveling Loaded	0.81	0.78	0.48	3.92	3.42	2.02
	Machine Traveling Unloaded	1.19	1.16	0.51	5.23	4.94	2.5
	Machine Working	0.7	0.67	0.31	7	6.47	3.42
	Machine Traveling while Loading	0.60	0.42	0.58	3.31	2.37	2.99
Data logger-based machine speed	Machine Traveling	2.54	2.52	0.93	12.09	11.67	4.24
	Machine Loading	0.56	0.51	0.28	5.66	5.08	3.1
	Machine Unloading	0.14	0.11	0.1	1.33	1.07	0.93

Despite the differences between the two classifications, the average total time and total fuel consumed per cycle obtained through the use of both classifications reflects the same average 3.25 liters of fuel consumption per cycle (with a median and a standard deviation of 3.2 and 1.11 liters, respectively), and the same average 19.09 minutes per cycle (with a median and a standard deviation of 18.82 and 6.65 minutes, respectively). In addition, the same variables were estimated also per each working site studied, reporting 19.02 minutes and 3.07 liters per cycle for Site A, 23.92 minutes and 2.67 liters per cycle for Site B, and 26.5 minutes and 4 liters per cycle for Site C. Furthermore, the average extraction distance was 314.84 meters, with an average of 355.67 meters corresponding to site A, 205.05 meters corresponding to site B, and 305.93 meters corresponding to site C.

Additionally, the kilograms of CO_2 equivalent emitted by the machine, while performing this study was calculated, based on the fuel consumption registered and the existent literature conversion values [30]. The total amount of CO_2 emitted was 8.67 kg CO_2 equivalent per cycle and 2.7-2.9 kg CO_2 equivalent per single cubic meter of timber extracted, assuming an extraction volume of 3 cubic meters per cycle.

Inferential statistics

Analysing the influence of the Average Slope and Extraction Distance over the Time and Fuel consumed per Cycle and Work Element (Machine Traveling Unloaded and Machine Traveling Loaded) on all 3 sites studied (Table 3.8). Overall, it can be observed how these variables have a significant influence (at 99.5% interval of confidence) over all response variables, except in the case of the time used by the machine to travel unloaded uphill. In this case, it can also be observed how even the variables included into the random effect have no significant influence on the modelling of this specific work element.

Also, it can be observed how all independent variables considered positively influence the response variables, except in the case of the ones included in the Intersection of the Time and Fuel, while the machine travelled uphill unloaded. The Intersects used in this study gather together all the different possible influences of the site, stand machine and operator. However, since the machine and the operator were the same during the duration of this study, if the site effect is tested as random slope in a generalized linear mixed-effect model, it returns a higher significance level than the random intercept obtained performing a generalized linear model.

Table 3.8. *Time and Fuel Efficiency models.*

Time Efficiency models	**Equations**	**Coefficient**	**Estimate**	**S.E.**	**t-value**	**p-value**
Generalized Lineal Model (GLM) of Time Consumption per Cycle	TCYCLE	Intersect	451.936	95.3	4.742	<0.001
		Average Slope (%)	47.241	6.279	7.524	<0.001
		Extraction Distance (m)	2.717	0.300	9.054	<0.001
Generalized Linear Model (GLM) of Time Consumption Unloaded (Machine Traveling Unloaded)	TUNLOADED	Intersect	84.17	69.63	1.209	0.228
		Average Slope (%)	4.054	4.146	0.978	0.329
		Distance Going	0.982	0.173	5.673	<0.001
Generalized Linear Model (GLM) of Time Consumption Loaded (Machine traveling loaded)	TLOADED	Intersect	-80.043	20.605	-3.885	<0.001
		Average Slope (%)	16.767	1.265	13.254	<0.001
		Distance Coming (m)	1.191	0.08	14.934	<0.001
Fuel Efficiency models	**Equations**	**Coefficient**	**Estimate**	**S.E.**	**t-value**	**p-value**
Generalized Linear Model (GLM) of Fuel Consumption per Cycle	FCYCLE	Intercept	0.958	0.104	9.18	<0.001
		Average Slope (%)	0.088	0.007	12.845	<0.001
		Extraction Distance (m)	0.008	<0.001	25.847	<0.001
Generalized Linear Model (GLM) of Fuel Consumption Unloaded (Machine Traveling Unloaded)	FUNLOADED	Intersect	-0.115	0.041	-2.8313	0.005
		Average Slope (%)	0.043	0.002	17.991	<0.001
		Distance Going	0.003	<0.001	35.366	<0.001
Generalized Linear Model (GLM) of Fuel Consumption Loaded (Machine traveling loaded)	FLOADED	Intersect	-0.146	0.047	-3.087	0.002
		Average Slope (%)	0.016	0.003	5.431	<0.001
		Distance Coming (m)	0.004	<0.001	24.310	<0.001

3.6.Discussion

Considering the main objective of this study, which aims to test the feasibility of utilizing standardized SAE J1939 data to estimate and quantify the most important parameters influencing machine performance and efficiency, it was possible to identify between 60 and 70% of the working cycles performed by the machine (278 over 23 working days). However, if only work cycle identification is considered, without considering also the identification of work elements within each work cycle, the percentage of the cycles identified over the total cycles performed by the machines increases to more than 82%. Moreover, regarding the time and fuel consumption per cycle (Figures 3.4 and 3.5), it was also possible to estimate the time and fuel usage for each cycle, which values reached 19.09 minutes and 3.25 liters per cycle respectively for an average extraction distance of 314.84 meters, and an estimated load of 3 cubic meters per cycle. Comparing these values with the values reported in similar studies [12], [28], [29], [31] and considering the particularities of each one of them, it can be seen how the values reported in this study align considerably with those reported by them.

Moreover, through the use of this ATS methodology it was also possible to identify the non-standard working cycles or days, as it can be observed in Figures 3.4 and 3.5, regarding the last two days of work on site B. Concerning those two days of work, when consulted with the machine`s operator, the feasibility of the ATS methodology was once again supported, due to the fact that the two days in question were days in which the machine was managing logs and wood material at the landing point, situated on an almost flat (1-3%) well-structured gravel road. This explains the almost non-existent variability in the time and fuel consumption during that period of two days.

Also, regarding the same figures (3.4 and 3.5) it can also be deduced that the extraction distance variable plays a higher influence over the extraction time than over the fuel consumption, since the slope of the line between consecutives days of work per site is almost constant and homogeneously distributed on Figure 3.4, while the same does not happen so clearly in Figure 3.5. This phenomenon could be the effect of the increase in the extraction distance, since the general slope of the terrain in this case was classify as flat, with a range between 0 and 3 % of slope, and the extracted specie and diameters of the same, where uniform inside the cutting area. Thus, it can be concluded that in the estimation of the fuel consumption per cycle, the slope in addition to the extraction distance influence´s is bigger than considering just the extraction distance variable´s influence.

As shown also in similar efficiency studies regarding skidders performance [12], [32], [33], [34], the most time and fuel demanding activity occurs when the machine is traveling, both loaded or unloaded (Table 3.6 and Figure 3.6), establishing the extraction distance from the landing point and the average slope of the skidding trails, as one of the most influencing variables in skidders performance and efficiency.

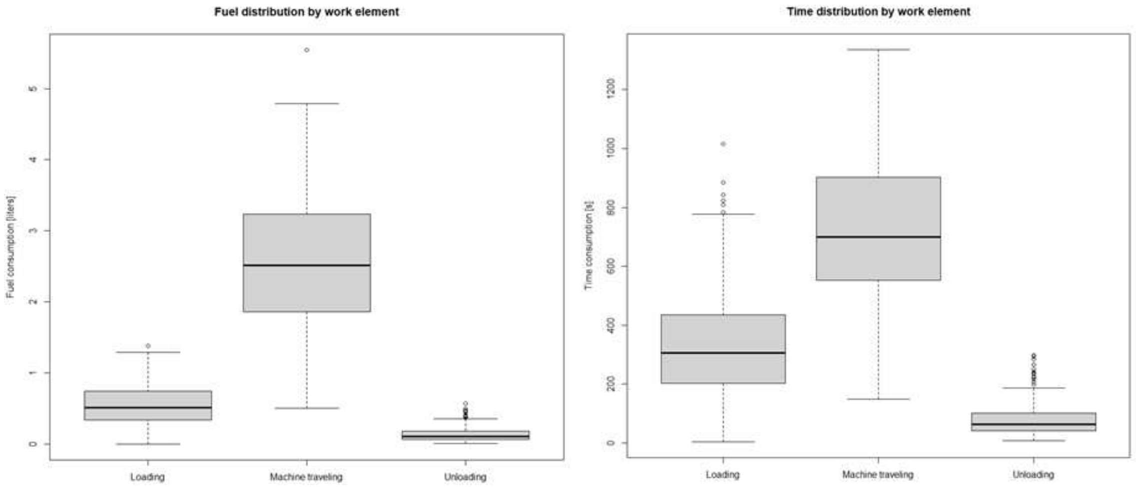

Figure 3.6. *Fuel consumption and time usage per working element.*

The influence of the above-mentioned variables (extraction distance and slope) over the time and fuel usage by the machine, in this study and using the ATS methodology, was not only proven, but also quantified by the development of the different Generalized Linear Models (Tables 3.4 and 3.8). From the models developed in this study, it can be observed how the main variables stated in similar studies (e.g. [12], [32], [33], [34]) and as common sense would also dictate (extraction distance and slope percentage), have a significant influence in the time and fuel usage regarding the working efficiency of the skidder. The only non-significant difference founded in this study, was regarding the effect of the variables included in the intercept and the average slope of the extraction trails, over the time that the machine was traveling unloaded uphill.

This could be explained by the behaviour of the machine operator, whose aim was to maximize the overall efficiency of each working cycle by traveling unloaded uphill as fast as the machine could go, regardless the slope or the high fuel consumption. The fuel consumed during this work phase could somehow also support this hypothesis, since it was the higher fuel consumption rate registered among all the different working phases (1.19 liters per cycle on average).

To conclude, from the use of this methodology (ATS through the use of the machine´s CAN-bus data), it was also possible to estimate the CO_2 equivalent emissions produced based on the fuel consumption, as a consequence of the normal work performed by the machine. The average amount of CO_2 equivalent registered was 8.67 kg CO_2 equivalent per cycle and 2.7-2.9 kg CO_2 equivalent per single cubic meter of timber extracted.

3.7.Conclusion

The feasibility of utilizing standardized SAE J1939 data obtained from forest machines was extensively proven by many researchers and by different forestry stakeholders such as machine manufacturers, contractors or forest managers, in an effort to improve the decision-making process and to ensure the sustainability of forest´s operations overall. This considering the difficult and sensitive dynamic of the modern forest ecosystems due to Climate Change (increase in the strength and frequency of extreme events, such as windthrows, severe droughts, biotic outbreaks, etc.).

In this study the feasibility of this methodology was tested on a forest extraction operation, performed by a skidder in a mountainous region, characterized by gentle to moderate slopes, rough terrain, and different stand compositions. The results obtained prove the feasibility of the ATS methodology, not only regarding the identification of the working cycles carried out by the machine (more than 82% of the cycles were successfully identified), but also its capability to identify the different work elements within each working cycle (between 60 and 70% of the total cycles performed by the machine during the period considered in this study), and as well as when delays or non-standard work cycles or work elements might have occurred.

These results allow on one side, to help the machine operator to be more efficient in detecting the possible bottlenecks or counterproductive situations and how to overcome them, while on the other, to predict the future impact and costs (based on the different statistical analysis, as shown in this study) of future extraction operations carried out by this machine or similar.

Another fundamental consequence of the implementation of this methodology is the possibility to carry out a time study of this machine or similar, without the need to perform it manually, with all the risks that it involves for the person in charge of performing it as well as regarding the possible human errors that have always to be considered, in these type of time studies. Nevertheless, the ATS methodology has also its limits of application, that can induce into making considerable mistakes (both over and under estimating the different parameters aimed to be analysed), thus critical thinking and good communication with the machine operator, is fundamental in order to obtain useful and accurate data. In order to increase the accuracy and feasibility of this methodology, further studies are needed, which may also consider the use of new technologies and software, such as the possible implementation of Machine Learning or Artificial Intelligence platforms, able to detect in an easier and accurate way the work cycles and work elements carried on by the machine, or the identification of the different non-standard work activities carried out.

3.8.References

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4. PAPER III: *Evaluating variables' influence on forwarder performance and fuel-efficiency in mountain salvage logging using an automatic work-element detection method*

Bacescu, N. M., Hueller S., Marchi L. & Grigolato, S. (2024). Submitted to Forests MDPI
Data are available through the following repository link:
http://researchdata.cab.unipd.it/id/eprint/659

4.1.Abstract

Extreme climate events are increasingly damaging forests, particularly in Europe's Alps. These disturbances lead to more damaged timber, necessitating rapid salvage operations to preserve timber value and protect ecosystems. However, salvage logging, though essential, raises concerns about its environmental impact, especially on soil conservation and forest regeneration. To mitigate these effects, best practices such as leaving logging residues and avoiding wet soils are recommended. Still, fuel efficiency remains a critical concern. This study focuses on addressing gaps in understanding forwarder productivity in salvage logging, considering factors such as assortment number, extraction distance, and payload. Utilizing Automatic Work-Element Detection (AWED) for data collection, the study enhances fuel efficiency analysis. Findings show that the average cycle time was 27.4 minutes, with 4.9 Liters of fuel consumed per cycle. Each cycle covered 241.3 meters, extracting 11.7 m^3 of timber, yielding a productivity rate of 31.6 m^3 per machine hour and a fuel efficiency of 0.4 Liters per $m^3$and per 100m. Traveling was the most time- and fuel-intensive task. Assortment type significantly impacted loading time and fuel consumption, with short sawlogs requiring fewer crane cycles. Key factors influencing productivity and fuel efficiency were, average log volume, distance, payload and slope.

Keywords: Cut-To-Length System, Forwarder-Based Extraction, Fuel, CO_2, Productivity

4.2.Introduction

Extreme events such as wildfires, insect outbreaks, storms, and floods are causing increasing damage to forest populations globally, with significant impacts in Europe, including the Alps [1], [2]. This situation has encouraged discussions, suggesting that forest ecosystems will have to deal with such extreme events more frequently in the future [1], [3], [4]. With the increasing incidence of these extreme events, there is a corresponding rise in the amount of damaged timber that must be salvaged. This situation necessitates rapid interventions to prevent the loss of timber value and to mitigate further damage to the ecosystem[5] [6], [7], [8], [9]. Salvage logging operations are common post-disturbance interventions, which consist of the removal of damaged trees. The recovery of damaged trees is the subject of ongoing discussions and research, aiming to mitigate the impact that the high intensity and scale of interventions have on the soil conservation [10] and on the regeneration capacity of forest stands [11], [12].

At the same time, when taking into account best practices for soil protection, such as leaving branches or in general logging residues along extraction trails [13] and avoiding operations on water-saturated soils [14], operation efficiency in terms of fuel consumption and production remains a key concern to ensure the competitiveness of forestry operations.

However, the application of Precision Forestry (PF) and Industry 4.0 (Fourth Industrial Revolution) concepts and tools, combined with a Big Data (BD) approach, has proven to be very useful in recent years supporting the decision-making process, for both forest managers and forest industry stakeholders [15], [16], [17], [18], [19], [20]. More precisely, regarding Forest Operations (FO), this situation has led to a co-evolution between the forest management and FO machines manufacturers and operators, resulting in the development of a wide variety of improvements for all parties [21]. Many developments have increased the ability to successfully harvest on steep terrain up to 75-85% slope, using ground-based equipment. Improvements have included additions such as self-levelling cabins [22], harvesters equipped with independently suspended tracks or wheels mounted on hydraulically driven arms [23], or forwarders with heavy-duty portal bogie axels with balancing system and significant modifications of carrier bases to improve traction and stability. Additionally, a major step-change has been the development of cable-assisted technology, this system can significantly increase the ability to operate on steep slopes and avoid soil damaging slip [24].

As a result of this co-evolution over the years, highly mechanized systems, like Cut-To-Length (CTL) and Whole-Tree (WT) systems, gained popularity becoming some of the most used harvesting systems, especially the CTL system in Europe [25], [26], [27]. In the CTL system the tree felling, processing (delimbing and bucking the tree stem) and measuring of the resulting logs (front-end diameter and length) is performed through the use of harvesters, while the woody material extracting process, from the forest to the roadside or to the landing areas is carried out using forwarders [15], [20]. However, the gained popularity and spread use of the CTL system, comes mainly from the fact that all the technological improvements mention above and many more (depending on each machine manufacturer), results in less but more specialized forests operators needed, with lower occupational hazards, lower harvesting costs and time, leading to an overall higher productivity and fuel efficiency [22]. Moreover, CTL system has proven to be one of the most suitable harvesting systems also in the case of salvage logging operations [28], [29], [30]. Despite the fact that salvage logging interventions have its benefits and drawbacks [6], [31], [32], [33]. When the site-specific characteristics are suitable for its implementation, fully mechanized systems (specially CTL system) are the most suitable technological alternative to carry on the recovery operation. The increasing volume of damaged timber necessitates not only swift recovery solutions but also heightened attention to the fuel efficiency.

In fact, while there is considerable knowledge about the fuel efficiency of timber recovery in normal conditions, less is understood about the fuel efficiency and safety of large-scale and intensive salvage logging operations under extraordinary conditions, particularly when these operations resemble complex, large-scale sites.

Productivity and fuel efficiency assessments of CTL systems are usually driven from the effective time and fuel consumption analysis of the machines involved in the harvesting operation. Realistic models developed from these variables can be applied to optimize harvesting operations with a future-oriented ultimate objective of increasing the resilience and resistance of the forest ecosystem against the challenges of Climate Change [34]. Timber extraction phase (from the forest to the landing areas) is the most time-consuming and expensive operation in the majority of the harvesting systems [35]. When it comes to CTL systems, the productivity and fuel efficiency of the forwarders is typically more complex to predict than for harvesters, due to the several additional independent variables involved, such as extraction distance, machine payload, total log concentration or number of products assortments being harvested [24], [34], [36], [37], [38]. Nevertheless, the latest technological advances have the potential to help foresters overcome these challenges, through the implementation of follow up studies and Automatic Work-Element Detection (AWED) [17]. Traditionally there has been a trade-off between representativeness and work element-specificity when compiling forwarding datasets, follow-up studies and standardized experiments representing the two extremes. However, follow-up-based studies, using the forest machines` On-Board Computers (OBC) and automated data loggers attached to machines` Controller Area Network (CAN)-bus offers nowadays minor to non-significant differences for main work elements detection, becoming thus, the automated data collection method, increasingly common in harvesting productivity studies [16], [17], [39], [40], [41], [42]. Although the number of assortments is already established as one of the most influencing variables when estimating forwarders´ productivity [26], [38] very few studies focused on the analysis of this variable [98], and none using the advantages of follow-up-based studies or AWED. The AWED methodology takes into account the OBC data to diagnose the engine status and running parameters. Thus, analysing how the registered parameters and additional sensors (GNSS, accelerometers, etc.) readings change, the different work elements can be detected almost automatically, through the use of BD tools and methodologies. The influence of the number of assortments extracted plays an important role especially in the case of salvage logging operations in which there are many types of assortments and each type has a different impact on the overall efficiency of the operation.

In order to fill this gap of knowledge and take advantage of the current accurate available data and exploitation of the AWED method, this work aims to evaluate the effect of the assortment on a large damaged site in the alpine context. With the final objectives of (i) identifying the influence of multiple product assortments over forwarder performance and (ii) evaluate the most significant variables affecting forwarding productivity and fuel efficiency in salvage logging operation and under real working conditions.

4.3.Materials and Methods

4.3.1. Case Study

The study was conducted in September 2023 in the north-east Italian Alps. The study area Figure 4.1, located in Trento province and bordering the Paneveggio Pale di San

Martino Natural Park, was affected by a bark beetle outbreak damaging the entire homogeneous even-aged spruce (Picea abies) stand. Further stand and site characteristics are described in Table 4.1.

Table 4.1. *Site and stand characteristics.*

Location	**Paneveggio**
Province	Trento
Elevation (m a.s.l.)	1 658.4
UTM (x; y) Coordinates (WGS84 UTM 32N)	(710 173; 5 131 749)
Total area (ha)	5
Damaged area (%)	100
Estimated damaged wood (m^3)	2 930
Average slope (%)	23.3
Species (% of volume)	
Picea abies	100

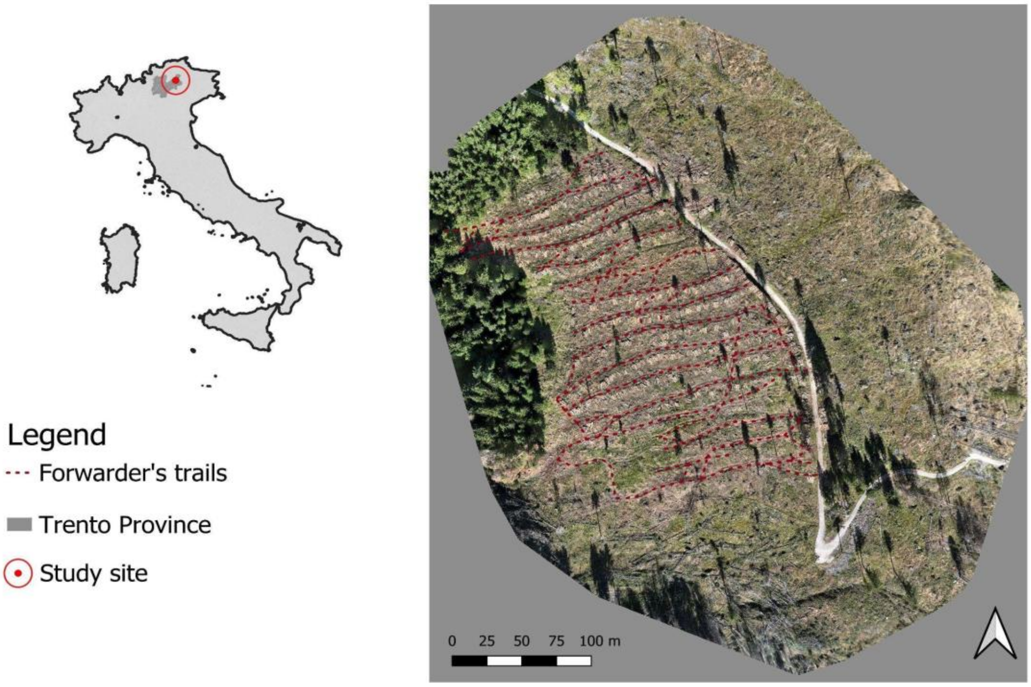

Figure 4.1. *Study area location at national level (right), and aerial image of the study area (left).*

4.3.2. *Machine Description*

Forwarders can be classified in three different groups according to their loading capacity: (i) light under 10 tones, (ii) medium from 10 up to 14 tones and (iii) heavy over 14 tones [29]. The forwarder used in this study was a John Deer 1210 E, and it falls into the medium size category with a loading capacity of 13 tones. It was equipped with an integrated synchronized winch, used by operator choice and usually on slopes over 27-30% and it also featured Olofsforst ECOTM tracks on the front bogies and Olofsforst BalticTM tracks on the rear bogies. Further machine details in Table 4.2.

Table 4.2. *Machine details and technical specifications.*

Model	**John Deere 1210 E**
Engine	John Deere 6068 PowerTech™ Plus turbocharged, charge air cooled, 6 cylinders, 6.8l-displacement
Power	140 kW (1900 rpm) / 189 SAE hp
Transmission	Hydrostatic-mechanical, 2-speed gearbox
Ground clearance	660 mm
Cylinders	6
Wheel number	8
Axles/Bogies	Heavy-duty Duraxle™ balanced-gear bogie axles at the front and rear. Hydromechanical differential lock at the front and rear.
Steering angle	44°
Weight empty	18 000 kg

4.3.3. *Data Analysis*

The study was carried out between September 8th and October 3rd 2023, comprising a total of 15.5 effective work days, during which period a CAN-bus data logger was connected to the OBC plug of the machine in order to record and store all available engine working parameters under the SAE J1939 standard. From all the machine parameters recorded, those considered useful for this study are shown in Table 4.3, and the sampling frequency for all of them was of one second. The data logger used in this study was the CANedge2 manufactured by CSS Electronics ("CAN Bus Data Loggers - Simple. Pro. Interoperable – CSS Electronics," n.d.). The CANedge2 enables stand-alone logging of the data from the CAN-bus of the machine to an SD memory card, and offers a range of configuration options such as message filtering, pre-scaling, transmit messages, cyclic logging, among others. Another advantage driven from the use of this technology is that it is a modular data logger, meaning that it is possible to connect different extension modules (sensors) to the main unit. In this study a CANmode.gps extension module was used in order to capture the position information of the machine while working. The CANmod.gps is a combined Global Navigation Satellite System (GNSS) and 3D Inertial Measurement Unit (IMU) sensor module, and it records the best possible positioning information by combining a variety of GNSS signals (GPS, GLONASS, Galileo, BeiDou).

Table 4.3. *Engine and GNSS parameters considered in this study, recorded with a frequency of 1 Hz.*

Machine Parameters	Format/Units
Date	dd/mm/yyyy
Hour	hh:mm:ss
Engine speed	rpm
Altitude	m a.s.l.
Distance trip	m
Engine fuel rate	l/h
Latitude	ON
Longitude	OE
Navigation based vehicle speed	m/s

Simultaneously, a manual time and motion study was carried out with the aim of (i) identifying the type of assortment extracted during each cycle, (ii) each cycle duration and (iii) estimation of the load volume through the use of photogrammetry. Individual load volume of the forwarder was estimated using a rear end picture of the complete load before unloading, and the diameter estimation was carried out by using AutoCAD software [104]. To perform the diameter calibration of each load, two scaled poles were attached on the back of the forwarder loading space on a similar plane to the logs end Figure 4.2. The manual study performed also included as a categorical (yes or no) variable the use of the synchronized winch.

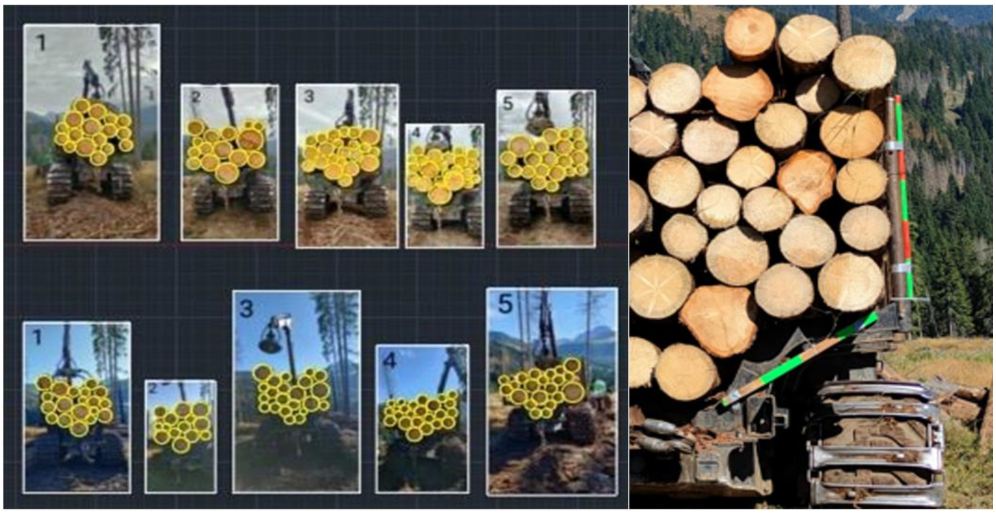

Figure 4.2. *Diameter measurements for volume estimation performed with AutoCAD (right) and scale poles for calibration of the volume estimations (left).*

The observational unit established for the statistical analysis was the working cycle. In addition, using QGIS 3.18.0 Zurich [45] software the landing area was delimited by a 20 meters buffer area from the centre of the road, in order to cover all the piles of material extracted (Figure 4.3).

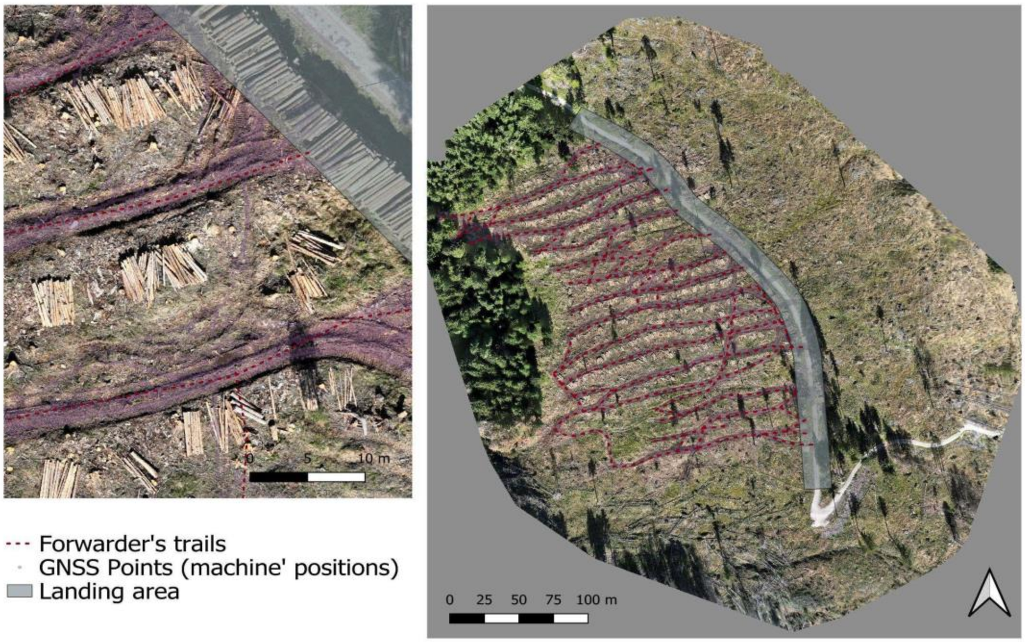

Figure 4.3. *Buffer area considered as landing area. Aerial overview of the skidding paths and the landing area buffer (left). Detail of forwarder paths, piles of to-be-extracted logs and logs pile included in the landing area (right).*

Thus, and adapting the R [46] code developed by [47], it was possible to automatically identify the different working elements within 195 out of 223 registered cycles (Table 4.4). The work elements classification was performed based on similar studies classifications and well-accepted[15], [16], [26], [38].

Moreover, the implementation of this AWED methodology enables the elimination of all non-productive periods (PMH0), which might have occurred, and allows an accurate estimation of time usage and fuel consumed.

Due to forwarding only one assortment type per cycle, changing skid trails to complete loads, and loading both going uphill and downhill, the Travel Unloaded and Travel Loaded, often described work elements in time studies, was considered in this study as one: Machine Traveling, in order to avoid possible time or fuel estimation errors. The same was applied to the extraction distance variable, which was studied as distance travelled by cycle instead.

Table 4.4. *Work elements detected while performing the AWED.*

Work element	**Description**
Machine Traveling	Begins when the machine starts to move to a new position from the landing area and ends when the boom starts to swing towards the first log to be extracted.
Machine Loading	Begins when the machine stops driving empty and the boom starts to swing towards a log to be extracted.
Machine Unloading	Begins when boom starts to swing, in order to unload the logs and ends when the boom rests in its original position and the machine starts to move again.
Other	Clearing ground; moving tops, branches and slash; stacking logs; refuel time (in shift); repair time (in shift); maintenance time (in shift); other delays (planning, rest…)

The influence of the assortment was studied on the different working cycles and working elements time and fuel consumption, as well as on the distance travelled by cycle, the average speed, and payload per cycle. The different wood assortments extracted, classified based on the different characteristics of the destination industry demands, and their characteristics are as shown in Table 4.5.

Table 4.5. *Study`s wood assortments characteristics.*

Assortment	**Characteristics**
Standard sawlogs	4.20m long logs, with both end diameters usually above 20 and under 60cm, with sawmill potential material as furniture or structural timber.
Small sawlogs	4.20m long logs, with both or one end diameter generally under 20cm, with poles fabrication potential.

Short sawlogs	3.30m long logs, with both or one end diameter generally over 60 cm, with sawmill potential material as furniture or structural timber.
Biomass	Tree tops, branches and defect logs (curved, split, damaged, etc.) for biomass purposes.

Furthermore, consulting the meteorological data of the study area, for the effective work days recorded, it was possible to establish a new variable defined as dry or wet soil. The wet soil condition was considered when the forwarder was operating during rainfall exceeding 2 mm/h and on the day following a rain event with more than 10 mm in total. The identification of work cycles under wet conditions was confirmed through direct field observations, while rainfall data with a 30-minute interval were obtained from the Paneveggio Weather Station, located 500 meters east of the worksite. The influence of this new variable was also studied over the same parameters as in the case of the assortment.

Finally, the average slope percentage per cycle was calculated (23.67%), as the result of the slope value of the 5 square meters cell size Digital Terrestrial Model (DTM) intersected with the machine positions registered for each cycle. From all the working cycles considered in this study, those with an average slope value equal or higher than 27% were isolated and within this subset the effect of the synchronized winch use was studied over the same parameters as in the case of the assortment and the dry/wet soil variables.

Ultimately, productivity and fuel efficiency models were calculated based on the higher significant variables registered influencing the overall productivity (m^3 /PMH0) and fuel efficiency (L/m^3 *100m).

4.3.4. Statistical analysis

The statistical analysis was carried out using the free software R (Version 4.1.2,) [46], interfaced with RStudio (RStudio, PBC, Boston, MA, USA). In the case of the assortment type and other variables (moisture of the soil and use of the synchronized winch) the normal distribution of the residuals was tested using Shapiro–Wilk normality test. Since the normality distribution hypothesis was rejected in all cases, to perform the comparison between the different groups within the different variables Kruskal-Wallis test for non-parametric data was applied. When the test showed significant differences a Dunn's Test was used, to pinpoint which specific means were significant from the others.

Delay-free productivity and fuel efficiency models were performed, and ANCOVA (Analysis of Variance) was conducted to evaluate how categorical factors (assortment, soil moisture and cable use) affect productivity and fuel efficiency, while controlling for the effect of continuous variables (average log volume, slope, travelled distance per cycle and payload). Average log volume in productivity studies is a fundamental predictor, however the relationship between this predictor and productivity may be complex and often non-linear. This is known as the "piece-size law" [48], [49] and power transformation of the parameter is well-accepted in order to deal with the nonlinearity. Implementing the "Box-Cox" function from the RStudio MASS package, the most suitable power value will be estimated and applied to the variable before developing the corresponding models. An F test was conducted to examine the goodness of fit of the models and to test the co-significance of the independent variables, which were also tested using a t test with a significant threshold settled at 95 % interval of confidence. Once the proper models have been established, sensitivity analysis will be included in order to highlight the effects found.

To cover the possible nested effect that the assortment variable may have over the productivity and the fuel efficiency predictive models, mixed effects models formulation will consider this variable as a "dummy" or random effect variable, in order to capture the possible group-level variation within the assortment. This analysis will be performed using "lme4" Rstudio package.

4.4.Results

A total of 5 337 minutes or approximately 89 PMH0 were recorded during the 195 considered cycles, on average 27.4 minutes per cycle, with the machine consuming a total of 962 liters of fuel, 4.9 liters on average per cycle, and extracting a total volume of woody material of 2 290 m^3. The average machine traveling time was 11.5 minutes per cycle with an average fuel consumption of 2.4 liters of fuel meanwhile, the average machine loading time was 7.9 minutes per cycle with an average fuel consumption of 1.4 liters per cycle, and the average unloading time was 5 minutes per cycle with an average fuel consumption of 0.9 liters per cycle. The average overall productivity registered was of 11.7 m^3 per cycle or 31.6 m^3 per PMH0, with an overall fuel efficiency of 0.5 liters per m^3 and cycle, and 0.2 liters per m^3 and 100 meters travelled. Furthermore, the average distance traveled per cycle was 241.3 meters, with an average traveling speed of 0.15 meters per second.

4.4.1. Assortment and other variables influence

Within the 195 cycles recorded and the 4 assortments extracted, 111 cycles were identified as standard sawlogs, 41 cycles as biomass, 22 cycles as small sawlogs and 21 cycles as short sawlogs. Table 4.6 compiles some basic descriptive statistics regarding the variables recorded specific to each assortment.

Table 4.6. *Overview of descriptive statistics of the variables examined among the different assortments, using cycle as observational unit.*

Variable	**Assortment**															
	Standard sawlogs				**Biomass**				**Small sawlogs**				**Short sawlogs**			
	Min.	**Mean**	**Max.**	**SD**	**Min.**	**Mean**	**Max.**	**SD**	**Min.**	**Mean**	**Max.**	**SD**	**Min.**	**Mean**	**Max.**	**SD**
Total time (min)	6.0	27.3	60	8	13	28.3	50	8.6	11	27.9	43	8.4	12	25.3	42	7.7
Time loading (min)	0.3	7.9	17.4	3	0.8	8.2	14.6	3.5	1.2	8.8	14.6	3.7	2	6.6	12.3	2.6
Time traveling (min)	2.7	11.3	26.3	4.2	4.7	12	23.1	4.3	5.4	11	19.1	4	6.2	12	19.2	4.2
Time unloading (min)	1.2	5	14.8	2.3	2	5.2	10.1	1.7	2.1	5.3	8.9	1.8	2.1	4.2	8.1	1.6
Total fuel (l)	1.8	4.8	10	1.6	2.7	5.2	10.3	1.6	2.6	5.2	8.4	1.5	1.6	4.5	7.8	1.7
Fuel loading (l)	0.1	1.4	3	0.5	0.2	1.4	2.7	0.6	0.2	1.5	2.8	0.6	0.3	1.1	2	0.5
Fuel traveling (l)	0.7	2.3	5.5	1.2	0.9	2.6	6.3	1.1	0.8	2.5	5.2	1.1	0.7	2.4	4.9	1.2
Fuel unloading (l)	0.2	0.9	2.5	0.4	0.4	0.9	1.9	0.3	0.3	0.9	1.5	0.3	0.4	0.7	1.3	0.3
Total distance (m)	45.6	226.2	468.6	107.3	102	271.7	574.9	109	96.6	254.4	493.8	105	114.2	245	464.5	100
Speed (m/s)	0.1	0.1	0.3	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.3	0.1
Payload (m^3)	5.6	14.1	22.8	2.5	2.8	6.8	13	2.6	3.9	11.4	15.3	2.5	2.8	9	13.3	2.2
Averg. Log volume (m^3)	0.2	0.5	1.1	0.1	0.1	0.2	0.6	0.1	0.1	0.2	0.5	0.1	0.3	0.4	0.6	0.1

Regarding the influence (significance at 95% interval of confidence) of the assortments type over the variables measured the following results were obtained (Table 4.7).

For those variables in which a significant difference was observed either at 95 or 90% interval of confidence, (Time loading, Time unloading, Fuel loading, Fuel unloading, Speed, Payload and Average log volume) a Dunn test using Bonferroni adjustment was performed, aiming to identify which assortments register the most significant difference on each variable.

Analysing the assortment type over the time consumed loading per cycle, significant differences were found between small and standard sawlogs vs. short sawlogs type of assortment, with adjusted p-values of 0.009 and 0.032 respectively. In the case of the time consumed unloading per cycle, the only significant difference was observed between biomass and small sawlogs vs. short sawlogs assortments, with a corresponding adjusted p-value of 0.053, although an adjusted p-value of 0.057 was observed between small vs. short sawlogs unloading times comparison.

In the case of the fuel consumption comparison among assortments, when analysing the fuel consumption while loading per cycle, significant differences were found between small vs. short sawlogs with adjusted p-value of 0.028, and no significant differences among assortments was observed when analysing the fuel consumption per cycle while unloading.

In the case of the total distance travelled by cycle analysis, no significant differences were observed between the different assortments, with the only mentionable difference of biomass vs. standard sawlogs analysis which reported an adjusted p-value of 0.065. Two comparisons, biomass and short sawlogs vs. standard sawlogs were the only ones registering significant difference, with adjusted p-values of 0.009 and 0.03 respectively, when performing the comparative analysis of the speed variable. Finally, when performing the payload and average log volume analysis, very strong significant differences were found between the standard sawlogs vs. the rest of the assortments with adjusted p-values less than 0.001 in the case of the payload, moreover, it was also found very strong significant differences between biomass vs. small sawlogs assortments with an adjusted p-value less than 0.001. Significant differences were found among all assortment levels in the case of the average log volume, except for the biomass vs. small sawlogs and standard vs. short sawlogs.

Table 4.7. *Assortment type significance influence over the variables considered.*

Variable	**p-value**
Total time (min)	0.604
Time loading (min)	0.022**
Time traveling (min)	0.702

Time unloading (min)	0.066*
Total fuel (l)	0.343
Fuel loading (l)	0.064*
Fuel traveling (l)	0.345
Fuel unloading (l)	0.094*
Total distance (m)	0.109
Speed (m/s)	0.003**
Payload (m^3)	< 0.001**
Averg. Log volume (m^3)	<0.001**

***Significant influence at 95% interval of confidence; *Significant variables at 90% interval of confidence.*

Additionally, visually representations were performed (Figure 4.4) of the distribution of the productivity (m3/PMH0) and fuel efficiency (L/m3*100m) among the different assortments' levels.

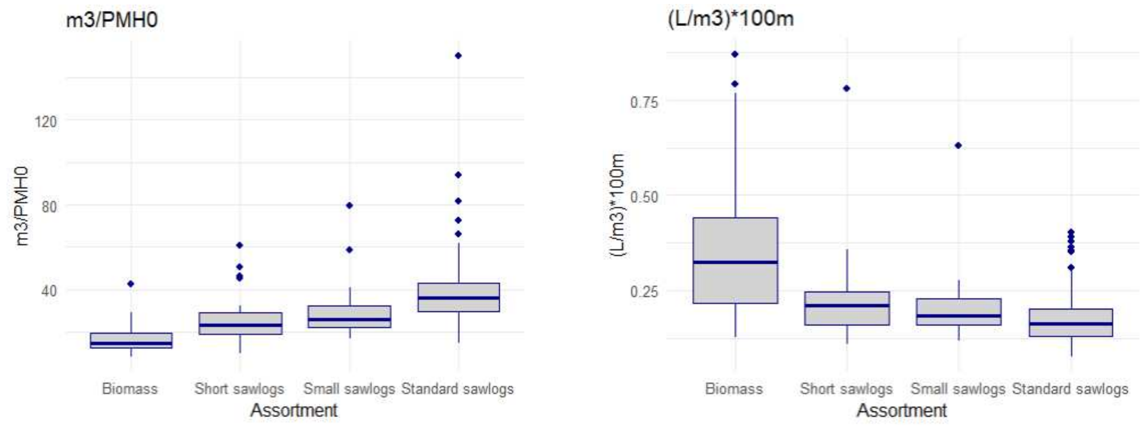

Figure 4.4. *Box-plot of productivity m3/PMH0 (left) and fuel efficiency L/m3*100m (right) distribution among the different assortments' levels.*

When analysing the wet/dry soil influence, it was possible to differentiate from the total 195 cycles, 54 as performed on wet soil and 141 as performed on dry soil. Its influence was studied over the same variables used above (except for the time and fuel consumption during the loading and unloading working phases). The results obtained were as shown in Table 4.8, where it can be observed that all variables studied are significantly influenced by the moisture of the soil except for the payload.

Table 4.8. *Descriptive statistics and significant influences of the wet/dry soil condition over different variables.*

Variable	**Wet**				**Dry**				**p-value**
	Min.	**Mean**	**Max.**	**SD**	**Min.**	**Mean**	**Max.**	**SD**	
Total time (min)	11.0	24.4	42.0	7	6.0	28.4	60.0	8.4	0.003**
Time traveling (min)	5	9.83	19.23	3.4	2.78	12.11	26.33	4.2	>0.001**
Total fuel (l)	1.65	4	7.78	1.3	1.81	5.29	10.28	1.5	>0.001**
Fuel traveling (l)	0.69	1.67	3.94	0.8	0.66	2.71	6.27	1.1	>0.001**
Total distance (m)	71.6	172.2	346.9	65.8	45.5	268	575	108.4	>0.001**
Speed (m/s)	0.05	0.12	0.23	0.1	0.05	0.16	0.3	0.1	>0.001**
Payload (m^3)	2.84	11.98	18.13	4	0.96	11.57	22.81	4	0.329
Averg. Log volume (m^3)	0.11	0.46	0.8	0.1	0.06	0.38	1.1	0.2	0.002**

***Significant influence at 95% interval of confidence.*

Finally, the effect of the synchronized winch use was studied by analyzing the average slope when the winch was used (34.36%) and establishing a lower slope filter of 27% on all cycles performed. Aiming in this way to achieve a more accurate comparison between the cycles when the winch was used and the cycles when it was not. This resulted in a total of 48 cycles from which 17 corresponded to the ones where the winch was used and 31 to those cycles where it was not. As seen in Table 4.9, no significant differences were found except for the influence over the payload, being always higher when the winch was used.

Table 4.9. *Descriptive statistics and significant influences of the synchronized winch effect over different variables.*

Variable	**Cable assisted**				**Without cable**				**p-value**
	Min.	**Mean**	**Max.**	**SD**	**Min.**	**Mean**	**Max.**	**SD**	
Total time (min)	6.02	27.57	51.02	11.4	6.02	28.4	60.02	6.5	0.358
Time traveling (min)	2.78	12.25	20.68	4.8	2.78	12.11	26.33	3.6	0.371
Total fuel (l)	2.16	5.44	10	2.1	1.81	5.29	10.28	1.4	1
Fuel traveling (l)	0.77	2.93	5.62	1.2	0.66	2.71	6.27	1.2	0.881
Total distance (m)	45.6	265.7	508.7	118.4	45.6	268	575	107.5	0.169
Speed (m/s)	0.07	0.16	0.26	0.1	0.05	0.16	0.3	0.1	0.284
Payload (m^3)	3.85	14.34	22.81	3.7	0.96	11.57	22.81	3.8	0.013**
Averg. Log volume (m^3)	0.1	0.4	0.8	0.1	0.1	0.4	0.7	0.2	0.574

***Significant influence at 95% interval of confidence.*

4.4.2. *Productivity and fuel efficiency analysis*

Regarding the productivity and the fuel efficiency modelling, the independent variables considered while fitting the models and performing the ANCOVA test were as shown in Table 4.10. In order to test the "piece-size law", power transformation was applied to the average log volume, obtaining an optimal power of e = 0.71. When fitting the productivity model, the transformed average log volume returns similar R2 and adjusted R2 values (0.64 and 0.63 respectively) than the non-transformed average log volume (0.64 and 0.63 respectively), thus in this case, the power transformation of the average log volume does not imply a significantly better fitting of the productivity model.

Table 4.10. *Descriptive statistics of the continuous and categorical independent variables considered in the productivity (m3/PMH0) model.*

Variable	**Unit**	**Min.**	**Average**	**Max.**	**S.D.**
Slope	%	6.34	23.67	56.03	7.7
Average log volume	m3	0.1	0.4	1.1	0.2
Traveled distance	m	45.58	241.59	574.48	107.3
Payload	m^3	2.77	11.74	22.81	3.9
Assortment	4 levels [Biomass, Standard sawlogs, Small sawlogs and Short sawlogs]				
Soil status	[Dry/ Wet]				
Cable assisted	[Yes/No]				

Linear productivity model was formulated (Table 4.11) considering only the significant independent variables, in order to avoid overfitting of the model. The resulting R2 was 0.64, and the adjusted R2 was 0.63. Additionally, the RSE (Residual Standard Error) was of 10 on 189 degrees of freedom, and the AIC (Akaike's Information Criterion) returned a value of 1460.5.

Table 4.11. *Explanatory variables founded to have a significant influence over the productivity (m3/PMH0) model prediction.*

Coefficient	**Estimate**	**Std. Error**	**t value**	**p-value**
Intercept	31	6.3	4.9	>0.001**
Average log volume ^e	16.5	4.1	4	>0.001**
Slope	0.48	0.1	4.9	>0.001**
Traveled distance	-0.07	0.007	-9.6	>0.001**
Payload	1.6	0.3	6.2	>0.001**
Soil status [Wet]	-4.2	1.8	-2.3	0.025**

**Significant influence at 95% interval of confidence.

Performing a sensitivity analysis on the productivity linear model, maintaining the mean values of all independent variables, except for the average log volume, which value was replaced with the net average log volume (0.4m3), the average biomass log volume (0.2m3) and the average standard log volume (0.5m3), it can be observed how this last variable responds accurately to the observed productivity (Figure 4.5). With the developed model it was also possible to analyse the influence of the average log volume over the rest of the variables considered over productivity (Figure 4.6).

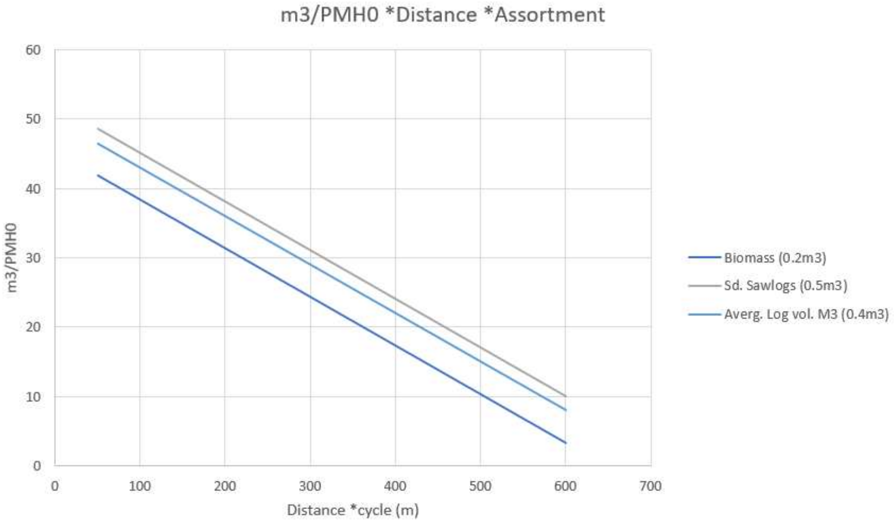

Figure 4.5. *Productivity of the forwarder (m3/PMH0) as a function of the average log volume (0.4m3), biomass average log volume (0.2m3) and standard log volume (0.5m3).*

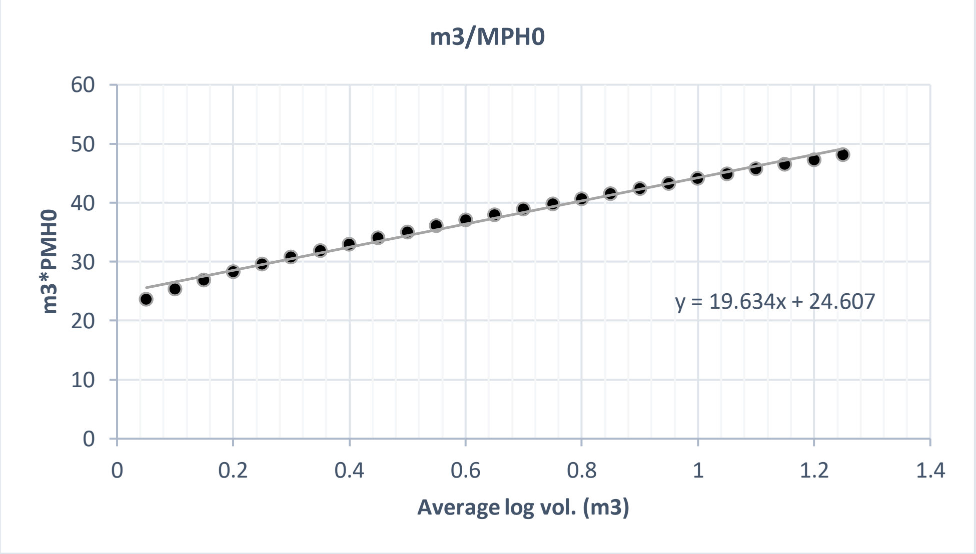

Figure 4.6. *Productivity of the forwarder (m3/PMH0) as a function of the average log volume.*

In the case of the linear fuel efficiency model (Table 4.12), the same independent variables as in the linear productivity model (Table 4.10) were tested to fit the model. In this case power transformation of the average log volume was unnecessary, firstly because when fitting the model this variable has no significant influence over the predicted one, and secondly due to even using the power transformed variable the R2 and the adjusted R2 of the model did not improve. In fact, the significant independent variables found for the fuel efficiency model prediction were the travelled distance, the use of the synchronized cable, the assortment (when extracting short sawlogs), and the payload.

The obtained R2 and adjusted R2 after fitting the fuel efficiency model were of 0.7 and 0.69 respectively, and the RSE (Residual Standard Error) was of 0.07 on 188 degrees of freedom. The AIC (Akaike's Information Criterion) returned a value of -448.7.

Table 4.12. *Explanatory variables founded to have a significant influence over the fuel efficiency (L/m3 *100m) model prediction.*

Coefficient	Estimate	Std. Error	t value	p-value
Intercept	0.7	0.02	30.1	>0.001**
Travelled distance	-0.0005	0.00005	-9.4	>0.001**
Cable assisted [Yes]	0.05	0.016	3.	0.003**
Assortment [Short sawlogs]	-0.07	0.02	-3.5	>0.001**
Payload	-0.026	0.002	-11.2	>0.001**

In order to test the possible nested effect of the assortment variable, productivity and fuel efficiency linear mixed effects models were formulated considering the assortment variable as "dummy" or random effect variable. In the case of the productivity linear mixed effects model, the use of the power transformation of the average log volume slightly increases (approx. 1-2%) the fitting of the model compared with the use of the non-transformed average log volume. Additional metrics, assessing the performance of the model were calculated (Table 4.14).

Table 4.13. *Explanatory variables founded to have a significant influence over the productivity mixed effects model prediction. In this case power transformation (e=0.71) of the average log volume was used.*

Coefficient	Estimate	Std. Error	t value	p-value
Intercept	31.7	6.6	4.8	>0.001
Average log volume ^ e	17.9	4.5	4	>0.001
Slope	0.5	0.1	4.9	>0.001
Travelled distance	-0.07	0.007	-9.7	>0.001
Payload	1.7	0.3	5.8	>0.001
Soil status [Wet]	-4	1.8	-2.2	0.03

Table 4.14. *Explanatory variables of random effect on the productivity mixed effects model prediction.*

Random effect	**Value**
Variance of Fixed Effects (σ^2)	99.2
Variance of Random Effects ($\tau00$)	3.5
Marginal R2/Conditional R2	0.65/0.67
Intraclass Correlation Coefficient (ICC)	0.056
Akaike's Information Criterion (AIC)	1465.3
N	4
Observations	195

Finally, regarding the fuel efficiency mixed effects model (Table 4.15 and 4.16), it can be observed how there are no significant differences, concerning the fitting of the model compared with the linear fuel efficiency model. When comparing the AIC of both linear and mixed effects models of the fuel efficiency it can be observed how in the case of the mixed effects fuel model the AIC is lower than in the case linear model (-400.6 and -448.7).

Table 4.15. *Explanatory variables founded to have a significant influence over the fuel efficiency mixed effects model prediction.*

Coefficient	**Estimate**	**Std. Error**	**t value**	**p-value**
Intercept	0.6	0.03	22.26	>0.001
Travelled distance	0.0004	0.00005	-9.5	>0.001
Cable assisted [Yes]	0.05	0.016	3.12	0.002
Payload	0.026	0.002	-12.15	>0.001

Table 4.16. *Explanatory variables of random effect on the fuel efficiency mixed effects model prediction.*

Random effect	**Value**
Variance of Fixed Effects (σ^2)	0.005

Variance of Random Effects (τ00)	0.0008
Marginal R2/Conditional R2	0.66/0.71
Intraclass Correlation Coefficient (ICC)	0.133
Akaike's Information Criterion (AIC)	-400.6
N	4
Observations	195

4.5.Discussion

Considering all cycles analysed in this study (without considering the assortment type extracted) it can be observed that the average time recorded per cycle was 27.4 minutes, with an average fuel consumption of 4.9 liters per cycle. The average travelled distance per cycle was 241.3 meters and the average volume extracted per cycle was 11.7m^3. This result leads to an overall productivity of the extraction operation of 31.6m^3 per MPH0, with an average fuel efficiency of 0.5 liters per m^3 and per cycle or 0.2 liters per m^3 and per 100 meters. This results, considering the site and machine specific characteristics, are in line with those reflected in other studies [15], [36], [50] being slightly different with[26] that reported 18.9m^3 per MPH0 for the same loading capacity forwarder, nevertheless this could be a consequence of the operation type carried on (selective cut in comparison with clear cut salvage logging).

When the analysis focused at work element level, the main finding shows, that the most time and fuel demanding work element was machine traveling, with an average 11.5 minutes and 2.4 liters per cycle, followed by machine loading work element with an average time and fuel consumption registered of 7.9 minutes and 1.4 liters per cycle. The least time and fuel consumption work element was machine unloading with an average 5 minutes and 0.9 liters per cycle registered. These results differ from those reported in similar studies where the main time and fuel demanding work element was machine loading [18], [36], [36]. This difference could be a result of the working process carried out by the machine in this study, as [38] stated, the different work elements time consumption is significantly influenced by the number of assortments in a load, lower number of assortments per load incurring in a higher time consumption. Since in this study the machine focused on loading only one assortment per cycle, thus having to travel longer distances to complete a full load, the time and fuel consumption during loading work element was smaller than the time and fuel consumption during traveling work element.

4.5.1. Assortment and other variables influence

Regarding the assortment type influence over the time consumption per cycle and work element, loading time per cycle showed significant differences between small and standard sawlogs vs. short sawlogs type of assortment. This difference could be explained by the characteristics of the short sawlogs itself, since its diameters were usually above 60 cm, being usually the bottom part of the stems, it took less time completing a load of this assortment type than completing a full loading cycle of the others, due to the reduce loading cycles required in the first case. In the case of the time consumed unloading per cycle, the only significant differences were observed between biomass and small sawlogs vs. short sawlogs assortments. This difference could be explained, as in the previous case, by the reduced crane cycles required while unloading a biomass or a small sawlogs load in comparison with unloading a short sawlogs load, higher in the last case.

In the case of the fuel consumption comparison among assortments, when analysing the fuel consumption while loading per cycle, significant differences were found between small vs. short sawlogs, and no significant differences among assortments was observed when analysing the fuel consumption per cycle while unloading or traveling work elements. The fuel consumption difference found while loading is a direct consequence of the higher crane cycles required to complete a load in the case of the short sawlogs compared to the other assortments (higher crane cycles per load incurs in higher time and thus higher fuel consumption). However, the fuel consumption difference was only significant between short vs. small sawlogs and not as in the time consumption while loading comparison, in which case there were significant differences between loading short sawlogs and the other assortments.

Regarding the total distance travelled by cycle analysis, no significant differences were observed between the different assortments, with the only mentionable difference of biomass vs. standard sawlogs analysis. The same comparison (biomass vs. standard sawlogs) and short sawlogs vs. standard sawlogs were the only one registering significant difference when performing the comparative analysis of the speed variable. These differences could be a result of the lower density of a full load of biomass or the short sawlogs, when compared with the density of a full load of standard sawlogs, being the difference the highest between these two assortment types. A lower density for the same load volume represents a lower weight of the payload, this allowing also to achieve higher speeds while traveling, due to the smaller engine power and grip required and smaller impact done on the skid trails.

Finally, when performing the payload analysis very strong significant differences were found between the standard sawlogs vs. the rest of the assortments. Moreover, it was also found very strong significant differences, in the case of the payload, between biomass vs. small sawlogs assortments with an adjusted p-value less than 0.001. Again, as in the previous case, the reason behind these differences could be explained by the different density of the different assortments.

In the case of the moisture of the soil influence, the results showed that the moisture had a significant influence over all parameters studied except for the payload. In fact, all parameters' values were higher when the soil was dry, except in the case of the payload. This could be explained by the individual choice of the operator that in the case of wet soil and to avoid greater impact on the soil, he prioritized collecting the closest to the landing point material. However, this result contrasts with the guidelines provided in [13] for forest soil protection, which recommend reducing payload loads in the case of wet soils

Finally, regarding the influence of the use of the synchronized winch, it can be observed how the only significant influence was registered on the case of the payload, this last one being significatively higher when the winch was used. However non-significant differences were observed also in the case of the time and fuel consumption while loading, being these ones also higher in the case of the cycles where the winch was used. This could be a result of the higher fuel efficiency achieved in the case of the use of the winch. This result is in line with those obtained by [51], nevertheless there are several additional safety aspects that are needed to be considered as for example the maximum allowed tensile force for the winch or the maximum tilt angle of the machine [52].

Considering the average log volume, it could be observed how significant differences were detected in all levels comparation, except for the biomass vs. small sawlogs and standard vs. short sawlogs. This could justify by analysing the measurements of the different assortments that does not showed any significant difference between them, because despite having similar average log volumes, the different assortments have different shapes and measures.

4.5.2. Productivity and fuel efficiency

In the case of the productivity prediction model, the most suitable independent variables found to explain the highest part of the variability were the slope, power transformed average log volume, travelled distance, payload and the moisture condition of the soil (when working in wet condition productivity drops 4 m^3 approx.). This result is in line with other productivity studies carried out [15], [26], [36]. However, the independent variables that were found to be the best predictors in the case of the fuel efficiency prediction were the travelled distance, payload, the use of the synchronized winch (which increases the fuel efficiency when used by approx. 0.05 L/m^3 and per 100m), and extracting short sawlogs (when extracting this type of assortment, the fuel efficiency drop by 0.07 approx.).

The use of the assortment type as a random effect in the case of the mixed effects models in the productivity despite having a slightly better fitting the mixed effects model, on average there was no significant difference between considering or not the assortment nested effect. This result may be associated at the low numbers of samples and its combinations, thus further analysis is needed for a deeper understanding of the assortment effect over productivity models, nevertheless, the fitting level of the model is more or less in line with those published by other authors [48], [49].

Considering the use of the assortment variable as a dummy, it does improve slightly the overall fitting of the fuel efficiency model (lower AIC in the mixed effect model than in the linear model), also achieving R2 values over 65% in all cases.

4.6.Conclusions

The present study analysed and evaluated the suitability and feasibility of the AWED methodology, with the final objectives of (i) identifying the influence of multiple product assortments over forwarder performance and (ii) evaluate the most significant variables affecting forwarding productivity and fuel efficiency in salvage logging operation and under real working conditions. Most findings are in line with similar studies carried out, however it also raises some new questions as for example the difference in the most time and fuel demanding work elements. Another challenge in understanding and conceptualizing the results of this study was the lack of similar studies when it comes to the assortment influence analysis and the use of the AWED methodology. As stated by [17], [39] the AWED methodology development, especially in the case of the forwarders, is still in its infancy, and the best results are obtained when combined manually and automatically collected data are analysed. Nevertheless, this could soon change due to the arise of a new game changer player, the AI (Artificial Intelligence) with its high capability of analysis and recognition of hidden states, especially in the case of the forwarders which equipped with fully sensorized cranes had unexplored capabilities of detecting work elements and much more.

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5. Final Discussion

The three publications presented in this thesis were designed and carried out with the final overall objective of setting the foundations for a robust standardized protocol for micro-metering fuel consumption in FO. Providing in this way, the necessary data to create more comparable fuel consumption and CO_2 emission models in fully and semi mechanize harvesting systems.

More specifically, regarding the first publication aim, to evaluate the benefits of automatic data collection via FMS, the FMS integrated with the GIS analysis and the use of a 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. 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 first publication, 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 was still a knowledge gap related to the way in which the different aspects involved in forest operations 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. In order to fill this gap of knowledge, in the following publications, additional technologies and measurements methods were apply.

In the case of the second publication, for example, a test version protocol was design, implemented, and its results were analysed, for the first time in a semi-mechanized harvesting system. The publication final aims being to test the Automated Time Study (ATS) methodology in a novel harvesting system, in varied mountainous terrains for fuel consumption and production models development.

From the models developed in this second publication, it could be observed how the extraction distance and slope percentage, have a significant influence in the time and fuel usage regarding the working efficiency of the skidder. As a consequence of the use of this methodology (ATS through the use of the machine´s CAN-bus data), it was also possible to estimate the CO_2 equivalent emissions produced based on the fuel consumption, as a consequence of the normal work performed by the machine.

The average amount of CO_2 equivalent registered was 8.67 kg CO_2 equivalent per cycle and 2.7-2.9 kg CO_2 equivalent per single cubic meter of timber extracted.

In this publication the results obtained prove the feasibility of the ATS methodology, not only regarding the identification of the working cycles carried out by the machine (more than 82% of the cycles were successfully identified), but also its capability to identify the different work elements within each working cycle (between 60 and 70% of the total cycles performed by the machine during the period considered in this study), and as well as when delays or non-standard work cycles or work elements might have occurred.

In a real-world scenario, the results allow on one side, to help the machine operator to be more efficient in detecting the possible bottlenecks or counterproductive situations and how to overcome them, while on the other, to predict the future impact and costs (based on the different statistical analysis, as shown in this study) of future extraction operations carried out by this machine or similar.

Nevertheless, the ATS methodology has also its limits of application, that can induce into making considerable mistakes (both over and under estimating the different parameters aimed to be analysed), thus critical thinking and good communication with the machine operator, is fundamental in order to obtain useful and accurate data.

In order to increase the accuracy and feasibility of this methodology, the third publication presented in this thesis, aims to utilize an improved data collection protocol and ATS methodology. The improved methodology, known as Automatic Work-Element Detection (AWED), aims to (i) identifying the influence of multiple product assortments over forwarder performance and (ii) evaluate the most significant variables affecting forwarding productivity and fuel efficiency in salvage logging operation and under real working conditions.

Regarding the assortment type influence over the time consumption per cycle and work element, loading time per cycle showed significant differences between small and standard sawlogs vs. short sawlogs type of assortment. In the case of the fuel consumption comparison among assortments, when analysing the fuel consumption while loading per cycle, significant differences were found between small vs. short sawlogs, and no significant differences among assortments was observed when analysing the fuel consumption per cycle while unloading or traveling work elements.

Regarding the total distance travelled by cycle analysis, no significant differences were observed between the different assortments, with the only mentionable difference of biomass vs. standard sawlogs analysis. The same comparison (biomass vs. standard sawlogs) and short sawlogs vs. standard sawlogs were the only one registering significant difference when performing the comparative analysis of the speed variable.

Finally, when performing the payload analysis very strong significant differences were found between the standard sawlogs vs. the rest of the assortments. Moreover, it was also found very strong significant differences, in the case of the payload, between biomass vs. small sawlogs assortments with an adjusted p-value less than 0.001.

In the case of the moisture of the soil influence, the results showed that the moisture had a significant influence over all parameters studied except for the payload. In fact, all parameters' values were higher when the soil was dry, except in the case of the payload.

Finally, regarding the influence of the use of the synchronized winch, it can be observed how the only significant influence was registered on the case of the payload, this last one being significatively higher when the winch was used. However non-significant differences were observed also in the case of the time and fuel consumption while loading, being these ones also higher in the case of the cycles where the winch was used. Considering the average log volume, it could be observed how significant differences were detected in all levels comparation, except for the biomass vs. small sawlogs and standard vs. short sawlogs.

In the case of the productivity prediction model, the most suitable independent variables found to explain the highest part of the variability were the slope, power transformed average log volume, travelled distance, payload and the moisture condition of the soil (when working in wet condition productivity drops 4 m^3 approx.). However, the independent variables that were found to be the best predictors in the case of the fuel efficiency prediction were the travelled distance, payload, the use of the synchronized winch (which increases the fuel efficiency when used by approx. 0.05 L/m^3 and per 100m), and extracting short sawlogs (when extracting this type of assortment, the fuel efficiency drop by 0.07 approx.).

Within the three publications presented, the general aim of this thesis to develop a robust standardized protocol for micro-metering fuel consumption in FO, that will provide the necessary data to create more comparable fuel consumption and CO_2 emission models in fully and semi mechanize harvesting systems was meet.

6. Final Conclusions

Considering that global natural resources are limited, achieving sustainable development methods and systems has become essential. Technology plays a critical role in linking human activity with natural resources, making the adoption of resource-efficient and environmentally sustainable technologies crucial to meet sustainable development goals [45]. This is particularly evident in the forestry sector, where eco-efficiency and sustainability principles are well-established through widespread forest certification standards and guidelines.

Another important reason to adopt sustainable and efficient FO harvesting methods is the increasing frequency of disturbances like wind damage, bark beetle infestations, and wildfires in European forests. These challenges have intensified throughout the 20th century, as reported by various studies [46], [47], [48], further underscoring the need for sustainable management practices in the forestry sector.

This thesis focusses on exploring the feasibility and reliability of the new technologies advancements driven from the implementation of the principle of Precision Forestry (PF) and Industry 4.0 with the aim to develop a robust standardized protocol for micro-metering fuel consumption in FO, that will provide the necessary data to create more comparable fuel consumption and CO_2 emission models in fully and semi mechanize harvesting systems.

In order to achieve this aim, a broad, large-scale assessment of fully mechanized harvesting systems using FMS, was carried out highlighting significant environmental benefits and enhanced FMS capabilities (Paper I). Moreover, a deeper, machine-specific analysis was performed, examining how external variables influence productivity and fuel consumption and so CO_2 emission per unit of wood processed or transported (Papers II and III). These studies contribute to understanding the direct environmental impacts, such as CO_2 emissions, and suggest pathways for improving operational efficiency through advanced data analysis techniques.

This being even more relevant since it sets the base for the implementation of Forestry 5.0. Forestry 5.0 embodies the next generation of forest management techniques and practices, leveraging advance AI (Artificial Intelligence) technologies to enhance FO sustainability, productivity and forest ecosystems resilience in the Climate Change scenario [49]. Forestry 5.0 represents a mayor game changing player since it integrates various AI techniques, crucial towards the development and implementation of autonomous harvesting machines. Moreover, unlike Industry 4.0 or Forestry 4.0, Forestry 5.0 aims to support humans and human decision-making process by building a Human Centered AI development, ensuring its safety and reliability.

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