Università degli Studi della Tuscia di Viterbo
Dipartimento di Scienze Agrarie e Forestali - DAFNE

Corso di Dottorato di Ricerca in
ENGINEERING FOR ENERGY AND ENVIRONMENT **- XXXVII ciclo**

TITOLO TESI DI DOTTORATO DI RICERCA

Sviluppo in ambiente GIS di un sistema di supporto alla progettazione di interventi di utilizzazioni forestali a basso impatto per una gestione forestale sostenibile

Settore scientifico-disciplinare
AGRI-03/C

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A.A. 2024/25

Ringraziamenti

La realizzazione di questo lavoro è stata resa possibile grazie al costante e prezioso supporto del mio Tutore Prof. Rodolfo Picchio e del Co-tutore Dott. Francesco Latterini fondamentali in questo percorso.

Riassunto

La crescente complessità della gestione forestale sostenibile in Italia e in contesti mediterranei analoghi richiede lo sviluppo di strumenti decisionali fondati scientificamente. Le operazioni forestali tradizionali sono spesso risultate carenti dal punto di vista analitico, portando a degrado ambientale, inefficienze nella gestione delle risorse e conflitti tra obiettivi economici ed ecologici. Questa ricerca di dottorato propone una metodologia integrata che combina i Sistemi Informativi Geografici (GIS) e il Processo Gerarchico Analitico (AHP) per supportare la selezione dei sistemi di esbosco sulla base delle caratteristiche ambientali e operative specifiche del sito.

Sono stati perseguiti tre obiettivi principali: (1) sviluppare e validare uno strumento basato su GIS-AHP per identificare il sistema di esbosco più idoneo a livello di particella di taglio, (2) valutarne l'applicabilità e la precisione in un'area forestale pubblica dell'Italia centrale utilizzando dati da piani di gestione e rilievi di campo, e (3) analizzare l'efficacia dell'indice "Depth-to-Water" (DTW) nell'individuare aree sensibili al disturbo del suolo causato dalle operazioni meccanizzate.

I risultati mostrano che il modello GIS-AHP migliora l'obiettività nella pianificazione forestale, mappando con precisione l'idoneità di forwarder, trattori con verricello e gru a cavo in base a sei criteri principali (es. pendenza, capacità portante del suolo, distanza di esbosco). Le mappe DTW si sono dimostrate efficaci nell'identificare zone vulnerabili dal punto di vista biologico e fisico, soprattutto in presenza di elevata umidità del suolo, dove il recupero post-intervento risulta più lento. Il confronto tra i dati del piano di gestione forestale e i rilievi di campo ha evidenziato discrepanze che sottolineano l'importanza del monitoraggio diretto e della gestione adattativa.

Questa ricerca dimostra che l'integrazione di GIS, AHP e analisi della sensibilità del suolo fornisce un quadro solido per operazioni forestali sostenibili dal punto di vista ecologico ed economico. La metodologia proposta favorisce decisioni di gestione forestale più informate e responsabili, ed è applicabile a diversi contesti ecologici.

Parole chiave: Gestione forestale sostenibile, GIS, AHP, Sistemi di esbosco, Sistemi di supporto alle decisioni, Selvicoltura di precisione

Abstract

The increasing complexity of sustainable forest management in Italy and similar Mediterranean contexts necessitates the development of scientifically grounded decision-making tools. Traditional forest operations have often lacked analytical rigor, leading to environmental degradation, inefficient resource use, and conflicts between economic and ecological goals. This PhD research proposes an integrated methodology combining Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP) to support the selection of timber harvesting systems based on site-specific environmental and operational variables.

Three main objectives were pursued: (1) to develop and validate a GIS-AHP-based tool for identifying the most suitable logging system at the cutting-block level, (2) to assess its applicability and precision in a public forest in central Italy using field and management plan data, and (3) to evaluate the use of Depth-to-Water (DTW) indices for identifying areas sensitive to soil disturbance. Results indicate that the GIS-AHP model enhances objectivity in forest planning, accurately mapping suitability for forwarders, cable skidders, and yarders based on six key criteria (e.g., slope, soil bearing capacity, extraction distance). DTW mapping was effective in identifying biologically and physically vulnerable zones, particularly in areas with high soil moisture, where post-harvest soil recovery was slower. The comparison between forest plan data and field surveys also highlighted discrepancies that underscore the value of ground-truthing and adaptive management.

This research demonstrates that integrating GIS, AHP, and soil sensitivity analysis offers a robust framework for ecologically and economically sustainable forest operations. The proposed methodology supports more informed and responsible forest management decisions and is scalable to diverse ecological regions.

Key words: Sustainable forest management, GIS, AHP, Timber extraction systems, Decision support system, Precision forestry

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1. INTRODUCTION

Forestry, both as a science and a practice, involves the management and cultivation of forests to ensure they continue to provide essential resources and environmental benefits over time. It includes a broad range of activities aimed at maintaining ecological balance and serving both the forest and surrounding communities. At its core, forestry is about sustaining forests for long-term productivity, health, and resilience—not just short-term gains. Historically, even ancient civilizations developed their own forest management techniques to coexist sustainably with nature.

Forest operations—the practical implementation of forest management—are generally divided into three main phases:

- Felling and processing
- Bunching and extraction
- Transport

Felling involves cutting down trees by removing them from their stumps. Processing, or bucking, refers to cutting the stem into commercially usable segments. Bunching is the movement of stems or assortments from the felling site to the extraction point. Extraction involves transporting these materials from the forest to the landing site, where they are then loaded onto heavy vehicles for delivery to processing facilities.

Modern technologies such as Geographic Information Systems (GIS) support forest operations by improving planning and decision-making. GIS allows for comprehensive landscape analysis by integrating various data sources, aiding land use management, road network planning, and selecting optimal logging strategies. These tools significantly enhance both the efficiency and safety of forestry operations.

The methods used for bunching and extraction vary depending on terrain, forest type, equipment availability, and safety requirements. GIS is instrumental in evaluating spatial data and tailoring operations accordingly. Levels of mechanization also vary—from manual labor to fully mechanized systems—and GIS plays a valuable role in organizing and optimizing these workflows, a concept central to Precision Forestry.

Forest mechanization refers to the integration of specialized machinery and equipment designed to perform key operations in the forestry sector, including felling, skidding, processing, and timber transport. The primary goals of mechanization are to increase operational efficiency, reduce production costs, and improve worker safety, while at the same time minimizing environmental impacts (FAO, 2022). Over recent decades, technological advances have progressively transformed forest operations, making them more sustainable and economically viable.

Depending on the degree of automation and the type of equipment used, forest mechanization is generally classified into three main levels: low, medium, and high. Low-level mechanization is characterized by a predominant reliance on manual labor and basic tools such as chainsaws, axes, and hand-operated winches. This level is typically found in small-scale operations and in mountainous or protected areas where minimizing soil disturbance and ecosystem impact is a key concern. Despite the advantage of low initial investment and reduced environmental interference, this approach is limited by low productivity, high labor intensity, and increased safety risks (Labelle & Lemmer, 2019).

Medium-level mechanization involves the use of semi-mechanized or towed machinery, such as motorized winches, forest tractors, and small skidders. It is often adopted by medium-sized forest enterprises and enables a balanced trade-off between productivity and environmental sustainability. This level improves worker ergonomics and efficiency but requires adequate training and infrastructure, such as forest road networks. The associated environmental impacts are moderate and depend greatly on operational planning and machine mobility (Spinelli, Lombardini, & Magagnotti, 2014).

High-level mechanization is characterized by the deployment of advanced, fully mechanized equipment such as harvesters, forwarders, processors, and grapple skidders. These technologies allow for the automation of most forest operations and are typically employed in large-scale or industrial forestry activities, especially on flat or gently sloping terrain. High mechanization levels contribute to significant increases in productivity and worker safety, and allow for greater traceability of wood products. However, they also involve considerable capital investment and a higher risk of soil compaction and ecological disturbance if not properly managed (Labelle & Lemmer, 2019; FAO, 2022).

Ultimately, the selection of an appropriate mechanization level must consider a variety of factors, including terrain characteristics, forest accessibility, operational scale, economic objectives, and environmental constraints. A well-structured and context-sensitive approach to forest mechanization is essential to ensure the long-term sustainability and efficiency of forest management operations.

1.1 PRECISION FORESTRY

In today's environmentally conscious society, forest management is increasingly complex and requires in-depth knowledge of ecological systems. Precision Forestry has emerged as a vital approach, integrating advanced tools to enhance forest resource management and support sustainable production. Forest technicians must collect accurate site data—including species composition, soil and geological characteristics, elevation, slope, precipitation, and microclimate—to inform decisions.

Precision Forestry emphasizes the integration of information and communication technologies (ICT) to modernize the national forest production system. It is not simply a list of tools or applications, but rather a multidisciplinary framework that offers innovative, tech-driven solutions to specific challenges in the forest sector (Ziesak, 2006). High-resolution spatial data enables repeatable processes that support forest development, protect riparian zones and habitats, and conserve environmental resources.

Precision Forestry connects decision-makers, environmental managers, and communities by aligning sustainable forest management practices with tools that improve both environmental and economic outcomes (Bruce Bare & Dean, 2001). The term "Precision Forestry" was formally introduced at the First Precision Forestry Symposium in 2001, organized by the University of Washington and the U.S. National Forest Service. It was defined as: "Precision forestry uses high-tech analytical and survey tools to support site-specific, economic, environmental, and sustainable decision-making for the forest sector, supporting the value chain from bare land to the end customer." (Bruce Bare & Dean, 2001)

Other definitions, such as that by Lubello & Cavalli (2006), describe it as the use of computer-based systems to improve forest management through more efficient data collection and decision support systems. It is often seen as a specialized discipline within the broader field of precision agriculture.

The goals of Precision Forestry include enhancing planning accuracy, improving implementation, and supporting multi-objective, sustainable forest management (Bruce Bare, 2003). The application of new technologies enables:

- Cost-effective analysis of complex forest data;
- Streamlined planning for operations using standardized routes;
- Integration among technicians, operators, policymakers, and communities via shared platforms like Web-GIS and mobile applications.

Precision Forestry can be categorized into three main application areas:

- Forest monitoring and planning
- Site-specific applications for forest and crop use
- Product tracking within the forest-wood supply chain

These categories often overlap, as many tools operate across scales and contexts. For instance, GIS can handle both highly localized site data and broad landscape-level information. This spatial and temporal scalability supports tasks ranging from individual tree assessments to global forest mapping.

Precision Forestry incorporates a suite of tools and technologies:

- GNSS (Global Navigation Satellite Systems), often integrated with inertial systems
- GIS software
- Remote sensing via satellites, aerial imagery, and drones
- Near-field survey tools
- Decision support systems

GNSS is especially critical for georeferencing in forest operations. Technological advancements have led to more accurate, compact, and cost-effective receivers, with data correction possible in real-time or post-processing.

GIS remains a cornerstone in forestry, enabling the visualization, collection, and analysis of geo-referenced data. The rise of mobile GIS and improvements in software and remote sensing have expanded field capabilities. For example, the State Forestry Corps and CREA developed a mobile GIS for navigation, data digitization, and real-time updates to a central server used in the National Forest Inventory (INFC, 2005).

In the Province of Trento, mobile GIS is used consistently for navigation and data collection at predefined sampling sites (Scrinzi et al., 2008, 2011). Similar systems were applied to field coding in the SIFTEC system at Castelporziano (Scrinzi & Clementel, 2015a; Colle, 2015). Complex mobile GIS platforms were also used in projects like FutMon for forest health monitoring (Colle et al., 2010, 2014) and CFS-PARTI, which introduced a customizable GIS for tracking spatial events in forests (Colle et al., 2009).

1.1.1 PRECISION FOREST HARVESTING

Precision Forest Harvesting is a key area within precision forestry that leverages GIS and advanced machinery to collect real-time data on tree species, wood quality, and assortments during felling and processing. This data can be used immediately for on-site decisions, such as tree sizing, or stored for later analysis, such as log value assessment. It can also be integrated with ground-level information and georeferenced datasets like road maps and timber volume maps. This integration allows forestry professionals to evaluate factors such as thinning intensity, tree density, and optimal machinery travel routes (Corona, 2017).

Digital maps play a crucial role in enhancing the efficiency of forestry operations. Operators can access real-time information on machine terminal displays, including environmentally restricted zones, water drainage areas, parcel boundaries, road networks, planned interventions, and trees marked for harvesting. These maps support both pre-planning—such as route analysis using GIS—and operational execution by incorporating sensor data from harvesting machines. The sensors monitor work times and site performance, contributing to increased operational efficiency (McDonald & Fulton, 2005; Pari & Civitarese, 2010; Nitami et al., 2011; Gallo & Mazzetto, 2013).

Despite technological progress, the integration of precision tools in forestry faces several challenges. Although many technologies have been developed, their application remains more common in environmental and ecological research than in practical forestry. Innovations such as bio-sensing, micro-electromechanical systems (MEMS), and sensor networks are transforming precision forestry by introducing new tools and materials. However, many remain in early stages of field deployment.

Adoption is also hindered by a slow uptake among end-users, often due to limited training. Without adequate instruction, workers may not fully understand how these tools can enhance productivity and safety in daily operations (Fardusi et al., 2017).

1.2 MULTI CRITERIA DECISION ANALYSIS (MCDA)

Multi-Criteria Decision Analysis (MCDA), as defined by Belton and Stewart (2002), is a collection of structured methodologies designed to assist individuals or groups in making decisions involving multiple, often conflicting criteria. MCDA is especially valuable in complex decision environments where diverse stakeholder interests must be balanced. The methodology generally follows four main phases:

1. Structuring the decision problem
2. Assessing the potential impacts of each alternative
3. Determining the decision-makers' preferences (values)
4. Evaluating and comparing the alternatives (Raiffa, 1968; Keeney, 1982; Belton & Stewart, 2002; Nordström, 2010)

Phase 1: Structuring the Decision Problem

The initial phase involves identifying the decision-makers (DMs), defining the decision criteria, and listing potential alternatives. The effectiveness of this stage is critical—poor structuring can compromise the entire analysis, regardless of the method used.

Many decisions involve multiple stakeholders who are either impacted by or responsible for implementing the final decision (Belton & Stewart, 2010). Identifying these stakeholders and determining the DMs is key. In group settings, the influence of each DM may be weighted based on their competence or relevance to the decision. These weights can be assigned in various ways:

- **Single DM Approach**: A central authority defines weights based on perceived competence (Ishizaka, 2013).
- **Participatory Approach**: All group members collaboratively determine weights.
- **Mathematical Approaches**: Weights may be derived from individual consistency (Chiclana et al., 2007; Cho & Cho, 2008), group consistency (Regan et al., 2006), or historical decision performance.

Once DMs are identified, a decision hierarchy is constructed. This typically includes the overall objective, main criteria (and any sub-criteria), and a set of alternatives (Keeney, 1992). Ideally, criteria should be essential, measurable, and operational. They should also be independent and non-overlapping to prevent bias in weighting (Ishizaka & Nemery, 2013).

A key challenge here is ensuring that the list of alternatives is comprehensive. In cases with continuous decision spaces, it may be difficult to identify satisfactory alternatives, potentially leading to stakeholder dissatisfaction. Techniques such as Strategic Options Development and Analysis (SODA) (Eden & Ackermann, 2001) or Soft Systems Methodology (SSM) (Checkland, 2001) can help clarify complex problems and generate suitable alternatives.

This stage is also vulnerable to cognitive and motivational biases. For instance, criteria with more sub-criteria often receive disproportionately high weights, unintentionally distorting the decision-making process (Montibeller & von Winterfeldt, 2015).

Phase 2: Assessing the Alternatives

Once the structure is established, each alternative must be assessed based on how it performs against the defined criteria. This evaluation can rely on quantitative data (measured, calculated, or simulated) or qualitative information (descriptive or expert-based).

Phase 3: Defining Criteria Weights

This phase focuses on establishing the relative importance of each criterion. Although objective methods such as the entropy method (Shannon & Weaver, 1947) and the importance criterion (Diakoulaki et al., 1995) exist, subjective weighting-based on stakeholder preferences—is more common and contextually relevant. In group settings, individual preferences are aggregated and adjusted according to the importance of each DM.

Phase 4: Evaluating and Comparing Alternatives

The final step involves evaluating and ranking alternatives using an appropriate MCDA method. These methods typically fall into three main categories:

- **Goal, Aspiration, or Reference-Level Methods**: Focus on minimizing the gap between actual performance and defined targets. Examples include Goal Programming (GP) (Charnes & Cooper, 1961), Compromise Programming (CP) (Zeleny, 1982), and TOPSIS (Hwang & Yoon, 1981).
- **Dominance Methods**: Use pairwise comparisons of alternatives across criteria. These are non-compensatory and typically don't provide a full ranking (Hokkanen & Salminen, 1997).
- **Value Measurement Methods**: Also known as compensatory methods, these include Multi-Attribute Utility Theory (MAUT), Simple Additive Weighting (SAW), and the Analytic Hierarchy Process (AHP). These allow for full aggregation of criteria and provide a complete ranking of alternatives.

Each method comes with its own strengths and limitations. For example, AHP and MAUT offer detailed insights but can be time-consuming, while methods like SMART provide simpler, more accessible options for collaborative decisions.

MCDA IN THE FORESTRY

Forestry decision-making is inherently complex, involving diverse and often conflicting economic, ecological, and social factors. These can range from long-term strategic concerns, such as land-use planning, to short-term operational issues like timber harvesting. Given the multi-scale and multi-dimensional nature of forestry decisions, MCDA methods are particularly well-suited to this domain. However, despite their proven success in other sectors, MCDA methods remain underutilized in forestry (Diaz-Balteiro & Romero, 2008). This may be due to limited awareness or the perception that MCDA tools are too abstract or complex.

Historically, forestry decisions were often made by a single authority, making the process relatively straightforward. Today, the involvement of various stakeholders—forest owners, local communities, environmental agencies, timber producers—requires reconciling competing priorities such as biodiversity conservation, economic returns, recreational use, and social equity.

The presence of these divergent interests creates challenges in stakeholder alignment and decision-making. MCDA methods offer a structured framework to evaluate trade-offs and develop balanced, transparent, and justifiable decisions.

Benefits of MCDA in Forestry

According to Belton & Stewart (2002) and Mendoza & Martins (2006), MCDA is particularly suited to forestry because it:

- Explicitly addresses multiple, often conflicting, criteria.
- Structures complex problems in a manageable way.
- Provides a platform for transparent dialogue among stakeholders.
- Integrates both quantitative and qualitative data.
- Supports collaborative and participatory planning.
- Encourages stakeholder engagement and consensus-building.
- Balances objective data with subjective value judgments.

By combining empirical evidence with stakeholder values, MCDA promotes better-informed, context-sensitive decisions that are aligned with sustainability goals.

Challenges and Future Directions

Despite its advantages, MCDA is not without limitations. Some methods can be complex and time-consuming, requiring substantial data inputs and stakeholder engagement. This can lead to perceptions of MCDA as a "black box," potentially undermining user trust.

Additionally, forestry decisions are often divided into strategic, tactical, and operational levels, but definitions of these timeframes vary across organizations (Carlsson et al., 2006; Borges et al., 2013). This inconsistency adds another layer of complexity to the decision-making process.

Nonetheless, the need for effective, transparent, and inclusive decision-making tools in forestry is only growing. As sustainability, climate resilience, and ecosystem services become more central to forest policy, MCDA—particularly when integrated into Decision Support Systems (DSS)—offers a promising path forward (Kangas & Kangas, 2005).

1.3 DECISION SUPPORT SYSTEM (DSS)

To make well-informed decisions, especially in complex scenarios, integrating Multi-Criteria Analysis (MCA) into computer-based decision support tools is often highly advantageous. These tools typically incorporate various modules — including databases, mathematical and simulation models, business logic, and Multi-Criteria Decision Analysis (MCDA). Systems that combine these components are known as Decision Support Systems (DSS).

DSS encompasses a wide range of systems and technologies designed to help decision-makers manage the complexities of the decision-making process. Although the term DSS covers a broad spectrum, there's no universally agreed-upon definition. As Keeney (1982) points out, it’s challenging to offer a precise explanation that fits all use cases. Still, scholars like Finlay (1994) describe DSS generally as "a computer-based system that assists the decision-making process." More specifically, Sprague and Carlson (1982) define it as "an interactive, flexible, and adaptable system primarily developed to support unstructured decision-making." Building on this, Power (1997) describes a DSS as an interactive information system that helps users locate, analyze, and synthesize key information — enhancing both the quality and speed of decisions, and even promoting better communication and learning.

In essence, DSS systems are designed to support complex decision problems that can’t be handled entirely by human judgment or by automated algorithms alone. Often, decision-making involves balancing multiple conflicting goals, and that’s where DSS truly shines — offering a structured process that evaluates alternatives and identifies the best course of action based on user-defined goals and constraints.

A critical factor for DSS success is the participatory nature of the process. Users, planners, and decision-makers must be involved throughout the system's development and use. Because users rarely know every requirement at the outset, ongoing engagement helps refine the problem understanding and solutions. Another key element is an intuitive user interface — without it, decision-makers may struggle to engage with the tool effectively.

Power (1997) categorizes DSS into five main types based on their primary function: communication-based, data-driven, document-based, knowledge-based, and model-based systems.

In practice, decision-making is rarely a solo task. It's often a multifaceted process involving multiple stakeholders with different — sometimes conflicting — priorities. So, the first step in developing a DSS is identifying the decision problem: understanding the current process, the stakeholders involved, their responsibilities, and any legal, political, or socio-economic constraints.

Typically, the decision-making framework includes:

1. **Control options** – Strategies or actions used to influence the system.
2. **Criteria** – Benchmarks used to measure performance.
3. **Objectives** – Optimization goals for each criterion.
4. **Constraints** – Conditions that must be satisfied for an option to be viable.

The main goal of a DSS is to help in selecting a control option that meets all constraints while optimizing the set objectives. This means carefully designing control options and accounting for external (uncontrollable) variables like weather or market trends. These factors influence outcomes, even though they can't be manipulated directly.

System performance is measured using indicators linked to each control option. Objectives often align with indicators that must be minimized or maximized. Constraints limit what values these indicators can take — they may be based on regulations, expert judgment, or real-world limitations. Internal variables that don't directly relate to criteria may also be subject to restrictions, ensuring practical feasibility.

Here’s how it works: different combinations of control options are generated and analyzed. Each one produces a unique system response, which is then assessed using performance indicators. Multi-criteria tools allow comparison, ranking, and selection of the most appropriate alternatives. When multiple goals are in play, assigning **weights** to each criterion is essential — this indicates their relative importance and helps prioritize trade-offs.

Once the problem is defined and structured, the final phase involves formalizing expectations, identifying feasible alternatives, and selecting the most promising one — ideally through multicriteria analysis. DSS applications in environmental management, such as those by Casini (2007) and Mocenni (2008), provide concrete examples of this process.

1.4 METOD AHP

The **Analytic Hierarchy Process (AHP)**, developed by Thomas Saaty in 1980, helps people make tough decisions by breaking them down into simpler comparisons. It's useful for setting priorities and choosing the best option when there are many criteria to consider.

AHP works by comparing elements in pairs—criteria or options—to figure out which is more important or better. This way, it captures both subjective opinions and objective data. It also checks whether the comparisons made are consistent, helping reduce errors or bias.

How AHP Works:

1. **Weighting the Criteria**: Each criterion is compared to the others to figure out how important it is. The more important, the higher the weight.
2. **Scoring the Options**: Each option is rated for how well it meets each criterion.
3. **Calculating Overall Scores**: The scores and weights are combined to give each option a final score. The option with the highest score is the best choice.

Table 1*: Saaty's Importance Scale*

Definition	**Importance**
Equal importance	1
Weak dominance	3
Strong dominance	5
Demonstrated dominance	7
Absolute dominance	9
Intermediate values (2, 4, 6, 8)	-

The ratings are placed in comparison tables to calculate the final scores. AHP also checks how consistent these ratings are.

Final Ranking:

1. Multiply the priority values for each option by the weights of the criteria.
2. The option with the highest total is the best one.

AHP works best when criteria are **independent**. It's easy to apply and very flexible, but the number of comparisons grows quickly with more criteria or options. To save time, software tools can automate parts of the process.

Software:

Programs like **Expert Choice** make AHP easier by helping with calculations and visualizations. Others, like **MPC©**, are designed for specific fields, like forestry.

Combining AHP with **GIS** can be especially powerful. For example, in forestry, this combo helps with prioritizing actions and managing resources more efficiently.

1.5 TRAFFICABILITY MAPS

While GIS and AHP can be integrated to develop DSS for the planning phase at the estate level, precision forest harvesting can go even to a deeper detail and provide cutting-block level DSS for supporting the planning of forest operations. In recent years, a significant application of precision forest harvesting technology, especially in Boreal regions, has been the development of soil trafficability maps for planning skid trails (or strip roads) (Hoffmann et al., 2022). These maps are designed to identify areas within a cutting block that are particularly sensitive to soil disturbance before the start of harvesting operations (Latterini et al., 2024c). By marking these areas, the maps help operators avoid them while operating machinery. A key focus is the Depth-to-Water (DTW) index, a concept initially developed and refined in Canada by a group of researchers from the University of New Brunswick's Faculty of Forestry and Environmental Management (Murphy et al., 2011, 2008, 2007). This approach relies on LiDAR-derived Digital Elevation Models (DEMs) with a resolution of at least 2 meters, which is crucial for generating trafficability maps based on the DTW index. The DTW index measures the vertical distance from a grid cell in a Digital Terrain Model (DTM) to the flow lines generated from DTM-based flow accumulation (Hoffmann et al., 2022). Its main advantage lies in the requirement of only a single input, a DTM with a resolution of 1–2 meters (Mohtashami et al., 2022a), and its capacity to model various soil moisture conditions by adjusting the Flow Initiation Area (FIA). The flow accumulation value for each grid cell is calculated based on its size and convergence with neighboring cells. A threshold is then set to determine the area required to initiate a flow line. For instance, low FIA values, such as 0.25 or 0.50 hectares, indicate wet soil conditions, while higher values, such as 16 hectares, represent drier soils or areas with higher soil-bearing capacity (Jones and Arp, 2019). In soil trafficability mapping, areas with a DTW index ≤1 are considered highly sensitive to soil disturbance, while those with a DTW index >1 are more resistant to the effects of ground-based forest operations. Numerous studies have shown a strong correlation between high soil moisture and low DTW index values (Ågren et al., 2021). However, studies on whether areas with a low DTW index are more prone to soil compaction and rutting have shown more mixed results (Mohtashami et al., 2017; Schönauer et al., 2021b, 2021a).

1.6 THE FOREST LAND PLANNING

The design of forest infrastructures is an evolving field, driven by the introduction of digital technologies such as **digital terrain models (DTM)**, **LiDAR**, **GNSS**, and **GIS**, which allow data to be collected, analyzed, and utilized with much greater precision than traditional methods. LiDAR, for instance, offers the ability to obtain accurate terrain information even in the presence of dense vegetation, reducing both the time and cost of surveying compared to traditional topographic methods (Ferraz et al., 2016). Additionally, the use of **GNSS** systems allows for real-time, continuous monitoring of position, proving essential for data collection and integration in the field, ensuring higher accuracy in the design of forest roads (Craven et al., 2014).

The adoption of advanced **GIS** systems also allows for the integration of various types of spatial data, such as topographic, geomorphological, and forest data, creating a complex and dynamic view of the road network and its interactions with the surrounding environment. For example, in projects like **FORCIP+**, the use of GIS has enabled the development of mobile applications that allow operators to collect and store data related to the road network directly in the field, using geodatabases accessible in real-time via **web-GIS** (FORCIP+, 2025). The implementation of such applications has significantly improved the efficiency of forest infrastructure management, also providing firefighting teams with immediate access to crucial information during rescue operations.

The integration of data collection, GIS-based analysis, and geolocation technologies has also improved the ability to assess accessibility in forest areas. The analysis of timber flows, which considers geomorphological characteristics and terrain slope, is now more accurate, thanks to the use of **distance models** and **multicriteria analysis** (MCDM). These models optimize infrastructure design, reducing operational costs and minimizing the risk of damage to existing roads, with a positive environmental impact (Ferraz et al., 2016). The **openness** maps, which calculate the accessibility of different areas relative to the road network, are particularly useful for identifying the most remote or difficult-to-reach zones, enabling targeted interventions and increasing overall forest management efficiency.

Forest road planning and design not only involve logistic and operational aspects but also **environmental sustainability**. The use of remote sensing techniques, such as **LiDAR**, helps monitor landscape changes and potential risk areas, improving decisions related to the construction of new roads, which must consider potential ecological and environmental impacts. The **LiDAR technology**, in particular, has proven to be highly effective in providing accurate data on soil morphology and vegetation, which are fundamental for designing forest infrastructures that minimize environmental impact.

Moreover, the progress in high-resolution **3D terrain modeling** through **DTM** has made it possible to more accurately predict soil stability and road safety, especially in areas prone to hydrogeological risk. The analysis of **excavation and fill volumes**, carried out with these models, allows for cost optimization and a reduction in the risks associated with soil instability. In fact, the accurate design of routes, supported by the analysis of soil behavior and terrain morphology, has become an essential practice for preventing natural disasters and ensuring user safety.

GIS technologies and **cloud-based applications**, such as those developed within the **FORCIP+** project, have also become crucial in emergency management, such as forest fires. The ability to consult data regarding the road network and terrain features in real time allows rescue teams to respond more effectively. Additionally, the use of **predictive models** to estimate timber flows and traffic loads on road sections helps identify the most vulnerable areas and plan targeted maintenance interventions. In this context, **ICT technologies** and **smart construction sites** are revolutionizing forest infrastructure design, increasing efficiency and reducing operational costs. The use of **GPS-equipped excavators** and real-time monitoring systems, for instance, has enabled more precise and safer management of construction sites, ensuring the timely completion of works without compromising quality (WSL/QGIS, 2025).

Finally, forest road design must also meet specific **ecological and conservation requirements**. In this sense, **decision support systems (DSS)**, integrating multicriteria analysis (MCDM) and **Analytic Hierarchy Process (AHP)**, are very useful tools for determining the need for new roads and assessing the environmental impact of proposed works. The **Autonomous Province of Trento** has adopted these tools to guide decisions regarding the creation of new infrastructures, taking into account various parameters, including soil productivity, the presence of natural habitats, and economic feasibility (Autonomous Province of Trento, 2025).

Summarizing, technological innovation has deedly transformed the field of forest infrastructure planning, enabling more precise, faster, and cost-effective management of forest resources. New technologies not only optimize project and operational processes but also contribute to more sustainable management and a significant reduction in environmental impact. The integration of GIS systems, LiDAR, GNSS, and advanced technologies such as **3D terrain models (DTM)** and **decision support systems (DSS)** has enabled the optimization of the design, maintenance, and management of the road network, opening up new opportunities for smarter and more responsible forest management.

1.7 THE PLANNING OF LOGGING ROADS AND TRACKS

The planning of logging routes is a crucial phase in forest management, as inadequate design can lead to significant environmental impacts and increase safety risks (Picchio et al.2020). Traditionally, this process relied on the operator's experience, but such an approach can prove inefficient, especially in complex contexts. Therefore, more rational planning is required, considering both the costs and the environmental impact associated with the construction of the routes. The use of technologies such as GIS systems and Digital Terrain Models (DTM) and Canopy Height Models (CHM) are revolutionizing this field, enabling more precise and informed planning.

DTM provides essential information about the terrain morphology, which is crucial for assessing the mobility of forestry machines and defining the profile of cable crane lines (Sterenczak e Moskalik 2015). CHM, on the other hand, offers details on the spatial distribution of tree crowns, the position of the largest trees, and, approximately, the size of the trunks. This data is essential for designing paths that minimize natural obstacles and reduce environmental impact on forest ecosystems.

The GIS modeling process for route planning includes several stages. The first step involves creating a trafficability map, which considers parameters such as the position of trees, terrain roughness, and sensitive areas to avoid, such as protected habitats or fragile soils. Raster reclassification is then applied to evaluate the area's trafficability (Bont e Heinimann 2012). Subsequently, the Least-Cost Path search is performed, which identifies the most efficient route in terms of time, taking into account the technical limitations of forestry machinery, such as maximum slopes. Another important aspect in route design is optimizing cable crane lines. By using GIS and high-resolution data, it is possible to simulate and define the optimal orientation and length of the crane lines, calculating altimetric profiles and the position of trees and tree crowns (Rizzi, 2012). These simulations help reduce operational costs and improve the overall efficiency of logging operations.

The SEILAPLAN tool, developed by the Swiss Federal Institute for Forest Research (WSL), is an example of the practical application of these technologies. This free plug-in for QGIS enables the automatic planning of cable crane lines. The required input includes selecting the starting and ending coordinates of the route, while the output provides the optimal position of the towers, the terrain profile, and the load trajectory, calculated based on technical parameters such as line length and rope characteristics.

In conclusion, the integration of GIS and DTM/CHM technologies in logging route design not only improves operational efficiency but also contributes to the environmental sustainability of forestry operations, reducing risks and ecological impact. Rational planning and the use of advanced tools represent a fundamental step towards more responsible, low-impact forest management.

2. ISSUES IN FOREST MANAGEMENT AND NEW SOLUTIONS

The need to develop a new methodology for planning and designing forest operations arises from a series of emerging and persistent problems in the forestry sector, both at the national and international levels. Traditionally, forest resource management in Italy has been characterized by practices that have often evolved based on practical experience and traditional knowledge, without an adequate analytical and decision-making support system to ensure a balance between environmental, economic, and social sustainability. This approach has led, in some cases, to suboptimal resource management with negative impacts on various fronts.

One of the main issues concerns the choice of the logging system, which represents one of the most delicate and complex operations in forest management. In Italy, the three most common systems (forwarder, winch, and cable yarder) are applied in very different contexts, but the selection of the most suitable system is often made empirically, without an objective evaluation of the parameters influencing the decision. Terrain characteristics, wood type, soil steepness, climatic conditions, and other local factors are not always systematically considered, which can lead to operational inefficiencies and, in some cases, environmental damage. For instance, the inappropriate use of a logging system on a very steep terrain could cause soil erosion, while a system that is too heavy might damage the surrounding vegetation.

Additionally, another critical aspect is the difficulty in balancing ecological and economic needs. If not properly planned, forestry operations can compromise biodiversity and disrupt the ecological balance of forest ecosystems. The need to optimize work times and operational costs often takes precedence over ecological goals, leading to conflicts between resource management and long-term sustainability. This scenario has led to the need for an approach that can rationally and scientifically integrate the multiple variables involved in forest management to prevent operational choices from compromising the ecosystem and the quality of forest management.

A parallel problem is the lack of decision-making tools that can integrate various pieces of information related to the specific characteristics of the territory. While GIS (Geographic Information Systems) are widely used in many areas of environmental management, their application in planning forestry operations has historically been limited in adapting strategic decisions to ecological conditions and specific economic needs. The ability to combine the analytical power of AHP (Analytic Hierarchy Process) with GIS systems is a recent solution that has the potential to address these issues by creating a methodology that is both objective and adaptable, capable of considering a wide range of variables and providing support for decisions that are sustainable from all perspectives.

Finally, the need to develop such a methodology is also linked to the increasing focus on social sustainability, an aspect often neglected in traditional forest management. Local communities that depend on forest resources for their livelihoods must be able to rely on equitable management that respects their well-being. Planning based on objective criteria, as proposed in this work, allows for consideration of the needs and expectations of forest owners and users, facilitating the creation of plans that meet economic needs without compromising long-term resources.

These issues, arising from traditional forest management practices, have therefore constituted the context and impetus for the development of a new planning and design methodology that not only addresses ecological and economic challenges but also proposes a model for more sustainable future forest management.

3. GOALS OF THIS PhD THESIS

Goal 1

The first objective of this study was to develop an integrated methodology that combines GIS (Geographic Information System) and AHP (Analytic Hierarchy Process) within a Forest Management Plan (FMP) to select the most suitable harvesting method based on the characteristics of the land and the specific needs of forest management. The application of this methodology aims to make the decision-making process more objective, rational, and data-driven, thus improving the effectiveness and sustainability of forestry operations.

The integration of GIS allows for detailed mapping and analysis of the geographical and environmental features of forest areas, while AHP provides a structured tool to evaluate and compare different logging methods based on various criteria, such as environmental impact, operational efficiency, and economic sustainability. The result of this combination is a forest management approach that considers not only operational needs but also ecological and social implications, optimizing choices based on a holistic and balanced view.

Therefore, the ultimate goal is to improve the decision-making process in forest resource management by providing a tool that can be applied globally, in different environmental contexts, to support informed and scientifically grounded choices. The objective of this study is to succinctly address the following question: is it possible to objectively identify the most suitable harvesting system for each cutting block within a forest management plan?

Goal 2

The second goal was to evaluate the reliability of an integrated approach based on GIS (Geographic Information System) and AHP (Analytic Hierarchy Process) for the development of a harvesting plan in a public area in central Italy. This approach was specifically designed for the Italian context, taking into account the local needs, the characteristics of the territory, and the forest harvesting methods commonly used in Italy. The integration of GIS with AHP aims to reduce the subjective bias typically found in the decisions of forest engineers, providing an objective method to select the most suitable harvesting system. The GIS-AHP model was applied using data from the local forest management plan and detailed information collected from field surveys in ten forest compartments, with the goal of optimizing operational decisions for harvesting activities in Italy. The related research question behind this goals was the following: how precise we can be in the identification of the most suitable harvesting system by using the data which are commonly available to forest practitioners in Central Italy?

Goal 3

The third objective of this study was to explore the potential effectiveness of soil trafficability maps (DTW) as a tool to identify areas most sensitive to disturbances caused by logging and timber movement operations, within the context of Mediterranean forests. The idea behind using DTW maps is that soil moisture significantly influences the compaction and damage that can result from heavy machinery during forestry operations. The DTW index, which measures the depth of water in the soil, could serve as a useful indicator of the soil's ability to withstand the passage of machinery without compromising its structure. If these hypotheses would be confirmed, DTW maps could provide a key resource for more accurately planning forestry operations, guiding machinery away from overly wet areas that are more vulnerable to damage, and focusing operations on terrain less susceptible to compaction. In theory, using these maps could significantly reduce the negative impact of timber harvesting operations, preventing irreversible soil damage and improving the sustainable management of forest resources. In the context of this study, it was hypothesized that areas with a low DTW index, indicating higher soil moisture, would be more sensitive to disturbances and biological damage. Based on these premises, it was assumed that in such areas, physical-chemical soil parameters like bulk density and penetration resistance could differ significantly compared to zones with a higher DTW index. Additionally, it was expected that areas with lower DTW would show lower values in the QBS-ar index, which measures the biological quality of soil through the biodiversity of the microarthropod community. The related research question is: are DTW maps reliable in detecting areas of a cutting block potentially more sensitive to machinery-induced soil disturbance.

Table 2 provides an overview of the studies and articles associated with each of the three objectives addressed in this research. This summary helps to contextualize the existing literature and highlights the relevant contributions that inform our analysis.

Table 2. Goal, article and conference paper

GOAL	ARTICLE	CONFERENCE PAPER
1	1. GIS-AHP Approach in Forest Logging Planning to Apply Sustainable Forest Operations. Latterini, F., Stefanoni, W., Venanzi, R., Tocci, D., Picchio, R. - (2022) FORESTS.	2. Statistical Validation Of Gis-Ahp Systems For Forest Harvesting Planning. Pari, L., Cozzolino, L., Stefanoni, W., Simone, B., Lazar, S., Picchio, R., Latterini, F., Latterini, F. - (2023) European Biomass Conference and Exhibition Proceedings
2	1. A Preliminary Validation and Assessment of a GIS Approach Related to Precision Forest Harvesting in Central Italy. Stefanoni, W., Tocci, D., Latterini, F., Venanzi, R., Gaglioppa, P., Pari, L., Picchio, R. - (2023) FORESTS.	
3	1. Depth-to-Water Maps to Identify Soil Areas That Are Potentially Sensitive to Logging Disturbance: Initial Evaluations in the Mediterranean Forest Context. Latterini, F., Venanzi, R., Tocci, D., Picchio, R. – (2022) LAND.	2. Precision Forest Harvesting Approach In The Utilization Of Riparian Forests. Latterini, F., Stefanoni, W., Lazar, S., Pari, L., Venanzi, R., Tocci, D., Picchio, R. - (2022) European Biomass Conference and Exhibition Proceedings.

4. MATERIALS AND METHODS

4.1 IDENTIFICATION OF ALTERNATIVE TIMBER EXTRACTION SYSTEMS

In the context of forest planning, the timber extraction operation is essential not only for the economic management of forest resources but also for minimizing environmental impacts and ensuring operator safety. The analysis conducted in this study focused on various timber extraction techniques, particularly those most suitable for Mediterranean forest environments. These systems, which have either already been implemented or are in advanced stages of experimentation, include two ground-based systems— a forwarder and a forest tractor equipped with a winch— and an aerial system, represented by a cable yarder equipped with an automatic carriage. The latter is particularly advantageous for operating on steep terrain, a distinctive feature of many Mediterranean forest landscapes. Although ground-based systems are widely used, their ability to operate on steep slopes is limited, where both extraction efficiency and soil protection may be compromised. On the other hand, the cable yarder offers greater versatility, reducing soil damage by transporting timber without direct contact with the ground, especially on sloping terrain (Marčeta et al., 2020).

4.2 DETERMINING ENVIRONMENTAL VARIABLES AND DETERMINANTS

The choice of the most suitable extraction system depends on a range of environmental and operational parameters that vary based on the site characteristics. The effectiveness of each system cannot be assessed in isolation from the context in which it is applied. Therefore, it is crucial to consider topographical variables, the type of forest intervention, soil conditions, and other specific features of the forest stand. This study identified six key parameters that influence the selection of an extraction system: slope, extraction distance, soil bearing capacity, yield, road density, and terrain roughness.

Each of these variables plays a crucial role in determining the optimal approach. For instance, slope is a decisive factor in system selection, as ground-based machinery is more suitable for moderate slopes, while a cable yarder is designed to handle steeper terrain (Borz et al., 2021; Ghaffariyan, 2021). Slope not only impacts productivity but also has environmental implications, as operations on steep terrain can lead to increased soil erosion and destabilization (Naghdi & Solgi, 2014). Additionally, increased slope poses operational difficulties, directly affecting operator safety (Picchio et al., 2020a).

Extraction distance refers to the distance between the timber collection site and the nearest forest road. The greater this distance, the higher the costs and time required for transportation. Moreover, this variable has a direct impact on ecological sustainability, as transport over long distances—particularly with ground-based or partially suspended aerial systems— can increase soil compaction and other environmental damages (Mariotti et al., 2020; Sealey & Van Rees, 2019). Operators also suffer, as more demanding working conditions increase fatigue and the risk of injuries (Picchio et al., 2019a). Soil bearing capacity is another crucial parameter that limits the use of certain extraction machines, as low bearing capacity soils do not allow the operation of heavy machinery without compromising the soil structure and reducing productivity. The use of inappropriate equipment on weak soils also increases the risk of accidents (Schweier & Ludowicy, 2020; Tavankar et al., 2021a). The yield parameter, which indicates the amount of timber that can be extracted from an area, is also critical. Generally, higher yield corresponds to higher productivity, but it also increases the risk of overexploitation if proper management practices are not adopted (Magagnotti et al., 2021; Marčeta et al., 2020). Finally, terrain roughness is a variable that cannot be ignored in forest operations, especially in mountainous areas. Operations on challenging terrain are among the riskiest in terms of workplace accidents, which can affect operators and compromise the entire operation (Enache et al., 2016).

The criteria outlined above are summarized in Table 3, which shows how each of them influences various aspects of sustainability: economic, environmental, and social.

***Table 3**. Identified criteria for determining the most suitable extraction system.*

Criterion	Acronym	Economy	Environment	Society
Slope (%)	S	✓	✓	✓
Extraction distance (m)	ED	✓	✓	✓
Soil bearing capacity (kPa)	SBC	✓	✓	✓
Yield (m^3 ha^{-1})	ETA	✓		
Road density (m ha^{-1})	ED	✓	✓	✓
Accidentality (%)	RG	✓		✓

4.3 DATA COLLECTION AND ASSIGNMENT OF RELATIVE WEIGHTS TO CRITERIA

A critical aspect of forest management is the communication between the various stakeholders involved in planning and implementing forest interventions. The lack of effective information flow between planners, field operators, and experts can slow progress and compromise decision-making efficiency. To bridge this gap, a questionnaire was developed to collect the relative weights of the identified criteria in the selection of the timber extraction system. This questionnaire was distributed to a group of forestry researchers (RTS), totaling 300 respondents, with 119 completed surveys returned.

The questionnaire was divided into three sections, each dedicated to one of the extraction systems analyzed. Each section included specific questions aimed at gathering expert opinions on the relative importance of each criterion. The data collected were then used to calculate the relative weights of the criteria, providing a quantitative basis for the evaluation and selection of the most suitable system for each specific context.

4.3.1 FORWARDER

The following questions were included in the survey regarding the forwarder:

1. In your opinion, how important is the parameter “slope of the terrain” in the extraction operation with a forwarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

2. In your opinion, how important is the parameter “extraction distance” (the average distance between felled trees and the nearest forest road) in the extraction operation with a forwarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

3. In your opinion, how important is the parameter “soil bearing capacity” in the extraction operation with a forwarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

4. In your opinion, how important is the parameter “amount of timber extracted” in the extraction operation with a forwarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

5. In your opinion, how important is the parameter “road density” (the ratio of the length of existing forest roads to the area of the parcel, expressed in m ha-1) in the extraction operation with a forwarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

6. In your opinion, how important is the parameter “accidentality” in the extraction operation with a forwarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

4.3.2 TRACTOR WITH FOREST WINCH

Based on the previous questionnaire, the following questions were addressed to experts regarding the tractor with a winch:

1. In your opinion, how important is the parameter “slope of the terrain” in the extraction operation with a tractor equipped with a forest winch? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

2. In your opinion, how important is the parameter “extraction distance” (the average distance between felled trees and the nearest forest road) in the extraction operation with a tractor equipped with a forest winch? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

3. In your opinion, how important is the parameter “soil bearing capacity” in the extraction operation with a tractor equipped with a forest winch? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

4. In your opinion, how important is the parameter "amount of timber extracted" in the extraction operation with a tractor equipped with a forest winch? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

5. In your opinion, how important is the parameter "road density" (the ratio of the length of existing forest roads to the area of the parcel, expressed in m ha-1) in the extraction operation with a tractor equipped with a forest winch? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

6. In your opinion, how important is the parameter "accidentality" in the extraction operation with a tractor equipped with a forest winch? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

4.3.3 CABLE YARDER SYSTEM

The last section of the questionnaire, though not less important, is focused on the aerial system analyzed, namely a cable yarder system. Again, the aim is to understand how each parameter affects the efficiency of the extraction operation with this system.

1. In your opinion, how important is the parameter "slope of the terrain" in the extraction operation with a cable yarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

2. In your opinion, how important is the parameter "extraction distance" (the average distance between felled trees and the nearest forest road) in the extraction operation with a cable yarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

3. In your opinion, how important is the parameter "soil bearing capacity" in the extraction operation with a cable yarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

1. In your opinion, how important is the parameter "amount of timber extracted" in the extraction operation with a cable yarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

5. In your opinion, how important is the parameter "road density" (the ratio of the length of existing forest roads to the area of the parcel, expressed in m ha-1) in the extraction operation with a cable yarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

6. In your opinion, how important is the parameter "accidentality" in the extraction operation with a cable yarder? (1 not important at all; 9 essential)

1___ 2___ 3___ 4___ 5___ 6___ 7___ 8___ 9___

Table 4: *Classes of suitability criteria for different logging systems*

Logging systems	**Parameter**											
	Slope		**Extraction distance**		**Soil bearing capacity**		**Yield**		**Road density**		**Accidentality**	
	Range (%)	**Score**	**Range (m)**	**Score**	**Range (kPa)**	**Score**	**Range (m^3 ha^{-1})**	**Score**	**Range (m ha^{-1})**	**Score**	**Range (%)**	**Score**
Forwarder	0-20	5	0-100	5	>80	5	> 200	5	>207	5	0-15	5
	20-40	4	100-200	5	60-80	4	100-200	4	138-207	4	15-30	5
	40-60	1	200-400	4	40-60	2	80-100	3	69-138	3	30-45	2
	> 60	0	>400	1	<40	0	< 80	1	<69	1	>45	0
Tractor with Forest Winch	0-20	5	0-100	5	>80	5	> 200	5	>207	5	0-15	5
	20-40	5	100-200	1	60-80	5	100-200	5	138-207	5	15-30	4
	40-60	4	200-400	0	40-60	3	80-100	4	69-138	4	30-45	3
	> 60	2	>400	0	<40	1	< 80	3	<69	2	>45	3
All terrain Cable Yarder	0-20	5	0-100	1	>80	5	> 200	5	>207	5	0-15	5
	20-40	5	100-200	2	60-80	5	100-200	5	138-207	5	15-30	5
	40-60	5	200-400	5	40-60	5	80-100	3	69-138	5	30-45	5
	> 60	5	>400	5	<40	5	< 80	1	<69	3	>45	5

To use the data obtained from the questionnaire, an additional table was developed, which assigns a range for each parameter and extraction system. The table uses different units of measurement suitable for each criterion, along with corresponding scores that range from one to five. This table is presented above as **Table 4**. In a further step the questionnaire was submitted to a group of 59 expert forest operators from various countries (OS). Results from the GIS-AHP procedure carried out with the input from RS was compared with those with the procedure with OS input data as a sensitivity analysis.

4.4 TRAFFICABILITY MAPS

The study examined the effects of forest harvesting operations on the physical, chemical, and biological properties of soil in two plots subjected to different mechanization levels (high and medium). The harvesting operations were carried out using a whole tree harvesting system (WTS), with chainsaw felling and mechanical extraction, including farm tractors equipped with winches and grapple skidders. The treated areas were 16.59 ha and 20.24 ha in size, with an average stand age of 19 years. To assess the impact of the operations on the soil, the Depth to Water table (DTW) index was used, which quantifies the soil's sensitivity to compaction in relation to its moisture content. The DTW index was derived from a Digital Terrain Model (DTM) obtained from high-resolution LiDAR data. The calculation of the index allowed for the identification of areas sensitive to compaction (DTW ≤ 1) and non-sensitive areas (DTW > 1), defining the zones for further analysis.

The DTW index represents the minimum elevation difference between surface flow channels and nearby landscape areas (Murphy et al. 2008). DTW values are zero in zones containing surface flow channels. As one moves away from these channels, DTW values increase, indicating reduced soil moisture further from surface waters. To create DTW maps, two thresholds must be defined: (1) flow initiation area (FIA), which is the catchment area needed to form flow channels; and (2) a DTW threshold value to classify soil as wet, typically set at 1. The primary advantage of DTW over other wetness indices is its ability to simulate various soil moisture scenarios by adjusting the FIA. Smaller FIAs (e.g., 0.25 ha) indicate higher soil moisture, while larger FIAs (e.g., 4 ha) suggest drier conditions.

The DTW map was generated from a 1 m DTM derived from LiDAR data provided by the Italian National Geodatabase. All procedures were carried out using the open-access software Quantum GIS

3.16, following the methodology proposed by Schönauer et al. (2021). Initially, the DTM was processed to remove local depressions. A flow direction tool was then used to identify the preferential water paths from each DTM cell. Flow channels were extracted from the DTM using a deterministic 8 (D8) flow accumulation tool, with an FIA value of 0.25 ha. This FIA value was chosen to simulate soil moisture conditions during the extraction period, which occurs from December to March, when soil moisture is highest in the Mediterranean context.

The output from the flow accumulation tool served as the basis for calculating the shortest vertical difference between each surface grid cell and adjacent flow paths using a lowest-cost function. The resulting raster is the DTW index map. This map was reclassified into a binary map, assigning a value of "1" to cells with a DTW index ≤1 and "0" to other cells. The reclassified map was then uploaded to a handheld Trimble Juno GNSS receiver for field surveys.

The experimental design involved comparing sensitive and non-sensitive areas to compaction within the plots treated with different mechanization levels. The harvested areas were classified into experimental treatments: (i) HM-DTW, sensitive areas in plots treated with high mechanization, (ii) HM, non-sensitive areas in plots treated with high mechanization, (iii) MM-DTW, sensitive areas in plots treated with medium mechanization, (iv) MM, non-sensitive areas in plots treated with medium mechanization, and (v) CON, a control area consisting of an oak coppice not harvested for the last 20 years. Soil physical and chemical parameters were measured through sampling at predefined points within the plots. Penetration resistance (MPa) and shear resistance (Mg m^{-2}) were measured in the top 3–10 cm of soil using a handheld specific instrument. Soil bulk density was determined by sampling the soil with a known-volume corer (100 cm^3), followed by weighing after oven drying at 105°C. Organic matter content was measured by incinerating the samples at 400°C for 4 hours, following standard methodology. The biological impact on the soil was assessed using the QBS-ar index, which quantifies soil biological quality based on the diversity and abundance of microarthropods. Microarthropods were extracted using the Berlese-Tüllgren funnel method and subsequently identified taxonomically (class for Myriapoda, order for Insecta, Chelicerata, and Crustacea) using a stereomicroscope. The QBS-ar score was calculated as the sum of the ecomorphological indices (EMI) of the microarthropod groups, ranging from 1 to 20 based on their adaptation to soil conditions. The data were statistically analyzed to assess the significance of differences between treatments. For normally distributed data, ANOVA was applied, while non-parametric Kruskal-Wallis tests were used for non-normal data. Post-hoc comparisons between groups were conducted using Tukey and Duncan tests. Additionally, non-metric multidimensional scaling (NMDS) was applied to visualize differences between experimental treatments, using the

Gower similarity measure for geometric representation of the data in low-dimensional space. In summary, the study integrated advanced geospatial techniques (DTM and DTW index calculation), physical-chemical measurements, and biological analyses to quantify the impacts of forest harvesting operations on soil properties, with particular attention to variations in compaction sensitivity and moisture conditions, providing useful information for the sustainable management of forest operations.

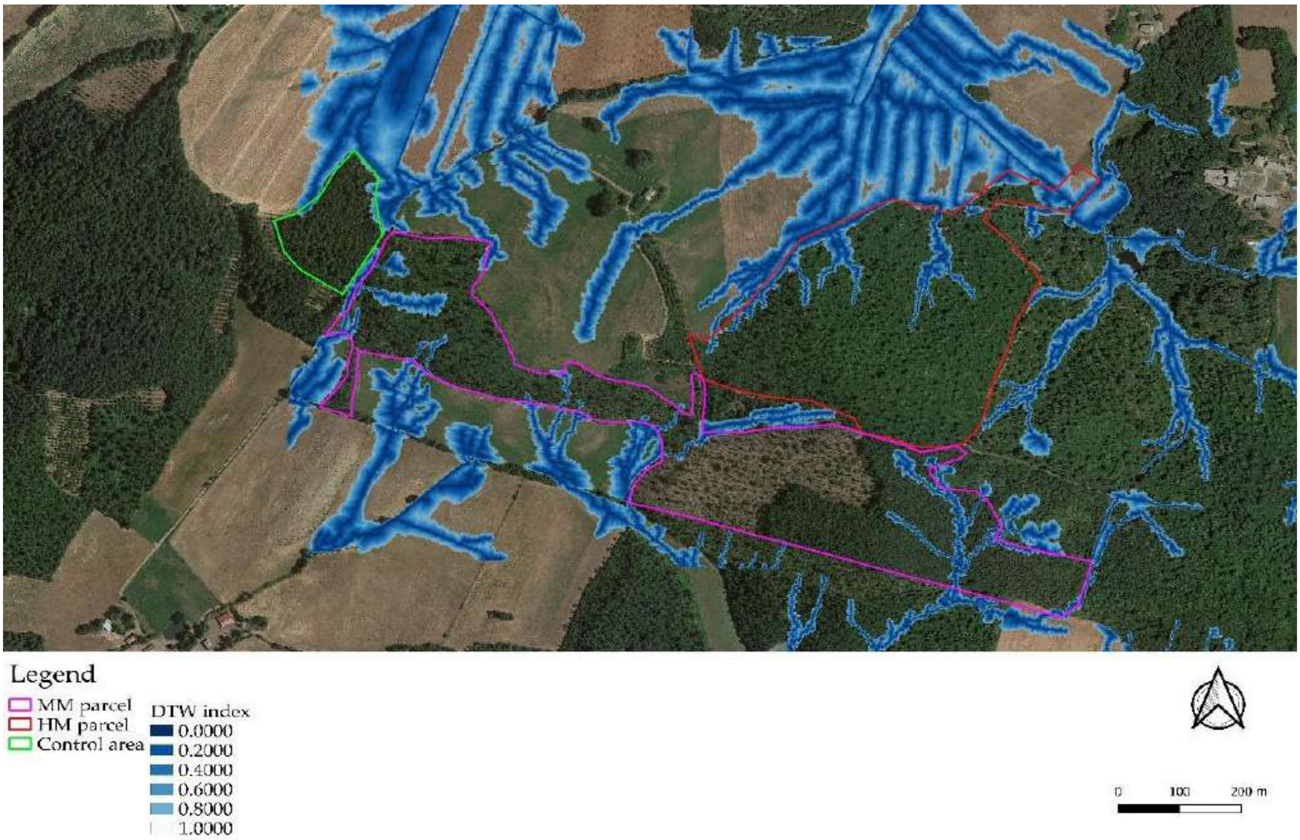

Figure 1. *Google satellite image of the study area (date 7 July 2019). The boundaries of the two parcels are reported in purple (MM—medium mechanisation level) and red (HM—high mechanisation level). Control area is reported in green. Blu zones represent the areas in which DTW index is ≤1.*

5. RESULTS

The three research goals that we set out to achieve with this study are detailed in the respective articles. However, they are also anticipated and summarized, highlighting the strengths and weaknesses of the various systems.

5.1. The first research goal result

1. **Technologies Used and GIS-AHP Methodology**: The study used the GIS-AHP (Analytic Hierarchy Process) methodology to analyze and select the best timber extraction methods in a forest area. The suitability maps, calculated with RTS (real-time system) and OS (optical survey) data, showed how different extraction technologies can be optimized based on various environmental parameters.
2. **Forwarder**: The forwarder showed a high level of suitability in the northern and southern parts of the study area, where the soils had good bearing capacity. However, the maximum suitability score for the forwarder was only 9 (out of 10), indicating that ideal conditions do not exist across the entire area.
3. **Cable Skidder**: The cable skidder performed similarly to the forwarder but showed a higher suitability score over a larger portion of the area, reaching a maximum score of 10 in several zones. It was recommended primarily in areas with high road density and low extraction distance.
4. **Cable Yarder**: The cable yarder showed highly variable suitability scores, with areas of both high suitability (score 10) and low suitability (score 3). It was recommended in areas with high timber extraction and low road density. This system showed a strong correlation with slope and extraction distance.
5. **Extraction Method Selection**:
    - With RTS data, the cable skidder was selected as the most suitable extraction method for 54.34% of the area, while the cable yarder and forwarder were chosen for 26.67% and 18.99%, respectively.
    - With OS data, the results were similar, but the selection of the cable yarder increased to 29.28%, while that of the forwarder decreased to 19.54%.
6. **Differences Between RTS and OS**: The differences between the two datasets mainly concern the weights assigned to selection criteria (e.g., road density and extraction distance), which

influenced the choice of extraction method in two specific sub-compartments (No. 8 and No. 69).

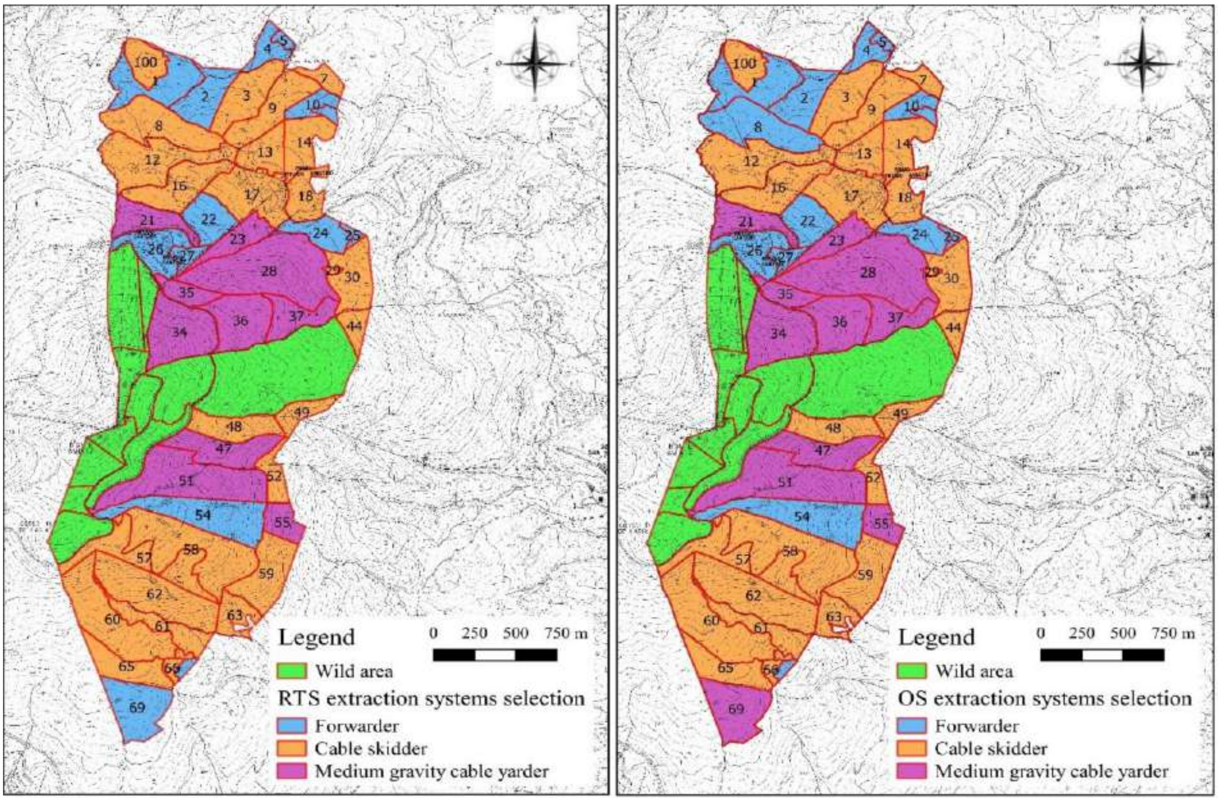

Figure 2. *RTS extraction method selection (on the* ***left****) and OS (on the* ***right****). As shown, the two predictions differ only for two sub-compartments (no. 8 and no. 69). In sub-compartment 8 (northwest of the study area), RTS indicated the cable skidder as an option, while OS selected the forwarder. In sub-compartment 69 (south of the study area), RTS selected the forwarder while OS the cable yarder.*

7. **Parameter Correlation**:
   - **Forwarder**: Shows a positive correlation with soil bearing capacity and timber extraction amount, but a negative correlation with slope and extraction distance.
   - **Cable Skidder**: Has a strong positive correlation with road density and a negative correlation with extraction distance.
   - **Cable Yarder**: Slope and extraction distance are the most influential parameters for the selection of this system.
8. **Statistical Tests**: The statistical tests (paired samples t-test) showed that the differences between RTS and OS were not statistically significant for the forwarder and cable skidder. However, the cable yarder showed a statistically significant difference, with a better score for the system based on OS.

In summary, the GIS-AHP methodology showed good consistency in selecting the most suitable extraction method, with differences between RTS and OS reflecting primarily the weight assigned to suitability criteria. The cable skidder emerged as the best choice for most of the area, while the cable yarder was selected for specific areas with certain terrain and infrastructure conditions.

Table 5. *Paired samples t test results. * indicates statistically significant differences (p < 0.05).*

Paired Samples *t* Test, Significance Level *p* < 0.05

	Average	Standard Deviation	*t*	*p*
Forwarder RTS	8	1.1		
Forwarder OS	8	1.2	−1.0000	0.322126
Cable skidder RTS	9	1.6		
Cable skidder OS	9	1.6	1.0000	0.322126
Medium gravity cable	8	1.5		
Medium gravity cable	9	1.5	−2.36247	0.022086 *

Table 6. *Results of Spearman correlation analysis. In bold, statistically significant results (p < 0.05).*

	Spearman R	***p* Level**
Forwarder and RD	0.244	0.084
Forwarder and ETA	**0.570**	**0.001**
Forwarder and RG	−0.045	0.751
Forwarder and SBC	**0.534**	**0.001**
Forwarder and S	**−0.485**	**0.001**
Forwarder and ED	**−0.300**	**0.033**
Cable Skidder and RD	**0.832**	**0.001**
Cable Skidder and ETA	**0.311**	**0.026**
Cable Skidder and RG	−0.011	0.938
Cable Skidder and SBC	0.160	0.262
Cable Skidder and S	−0.240	0.090
Cable Skidder and ED	**−0.856**	**0.001**
Cable Yarder and RD	−0.220	0.121
Cable Yarder and ETA	0.169	0.236
Cable Yarder and RG	−0.261	0.064
Cable Yarder and SBC	−0.078	0.589
Cable Yarder and S	**0.432**	**0.002**
Cable Yarder and ED	**0.370**	**0.008**

The choice of a logging system in forest operations is complex, as it is influenced by multiple factors. This study considers three systems suitable for Mediterranean contexts: two ground-based (forwarder and tractor with winch) and one aerial (three-cable crane with automatic carriage). Six key variables were identified: slope, extraction distance, soil bearing capacity, road density, and accident risk. These criteria influence the choice of the system in relation to the sustainability of the intervention.

Table 7: *Criteria identified for the selection of the optimal extraction system.*

Criterion	**Acro- nym**	**Economy**	**Environ- ment**	**Society**
Slope (%)	S	✓	✓	✓
extraction distance (m)	ED	✓	✓	✓
Soil Bearing Capacity (kPa)	SBC	✓	✓	✓
Amount of biomass (m^3 ha^{-1})	ETA	✓		
Road density (m ha^{-1})	ED	✓	✓	✓
Acciden- tality (%)	RG	✓		✓

A questionnaire was developed to collect experts' opinions on the relevance of criteria for various logging systems. The questionnaire, submitted to 300 experts, received 119 responses. The data collected were used to create pairwise comparison matrices, determining the relative weights of the criteria in the choice of the logging system. These weights reflect the importance of each criterion, and their sum equals 1. Another important parameter is the Consistency Ratio (CR), which verifies the reliability of the AHP results: if the CR is greater than 0.1, the weights are considered unreliable.

Table 8: *Relative weights and CR coefficient*

Forwarder		
Criterion	**Weights**	**CR**
Slope (%)	0,143	0,0001
extraction distance (m)	0,143	
Soil Bearing Capacity (kPa)	0,286	
Amount of biomass (m^3 ha^{-1})	0,143	
Road density (m ha^{-1})	0,143	
Accidentality (%)	0,143	

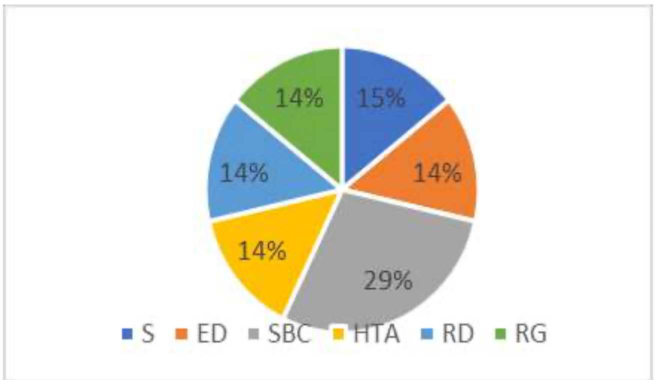

Figure 3: *Chart of relative weights percentages for forwarder*

Table 9: relative weights and CR coefficient

Tractor equipped with forestry winch		
Criterion	**Weights**	**CR**
Slope (%)	0,136	0,0002
extraction distance (m)	0,259	
Soil Bearing Capacity (kPa)	0,136	
Amount of biomass (m^3 ha^{-1})	0,075	
Road density (m ha^{-1})	0,259	
Accidentality (%)	0,136	

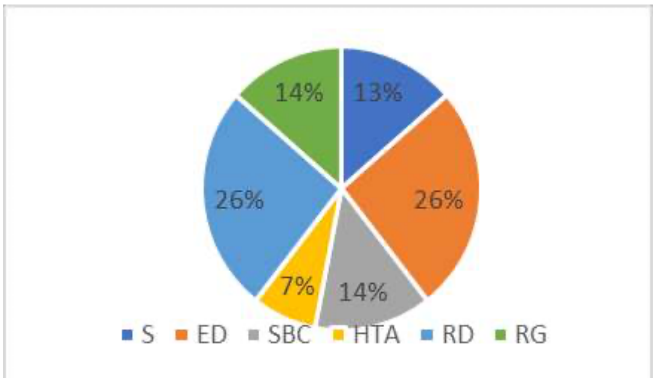

Figure 4: *Chart of relative weights percentages for tractor equipped with forestry winch*

Table 10: *Relative weights and CR coefficient*

Three cable crane equipped with automatic trolley		
Criterion	**Weights**	**CR**
Slope (%)	0,161	
extraction distance (m)	0,161	
Soil Bearing Capacity (kPa)	0,06	
Amount of biomass (m^3 ha^{-1})	0,399	
Road density (m ha^{-1})	0,161	0,01
Accidentality (%)	0,06	

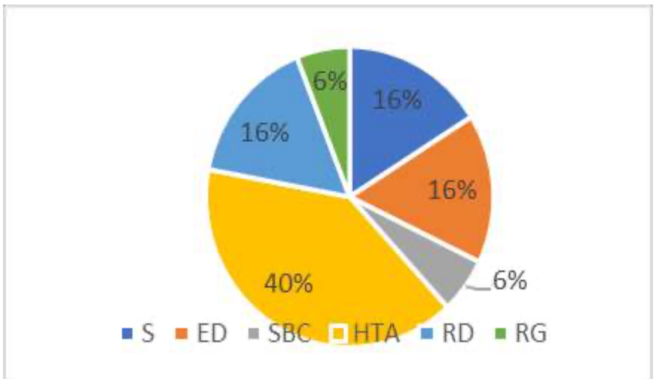

Figure 5: *Chart of relative weights percentages for Three cable crane equipped with automatic trolley*

5.2. The second research goal result

The study aimed to identify the most suitable extraction system for the cutting blocks in a specific forest area, using a GIS-AHP procedure based on data from the Forest Management Plan (FMP) and field surveys. The main results highlighted that forwarders were identified as the predominant extraction system, recommended for 64% of the cutting blocks, corresponding to 77% of the total area studied. Cable skidders were considered the most suitable alternative for 24% of the cutting blocks, particularly in areas with a low amount of extracted timber and a favorable location relative to the existing road network. All-terrain cable yarders were suggested only for 12% of the cutting blocks, which is 8.75% of the surface area, in zones with low soil-bearing capacity, a higher volume of extracted timber, or where the management plan provides for coppicing with 80-90 standards per hectare. However, when comparing the data from the forest management plan with the results of the field surveys, some significant differences emerged. In particular, three cutting blocks (31-1, 33-1, and 65-3) had a change in the recommended extraction system, shifting from forwarder to cable skidder, due to variations in key variables such as slope, extracted timber volume, and extraction distance. These changes reflect the sensitivity of the extraction system choice to factors like topography and timber distribution in the area. Statistical analyses showed significant differences in the suitability values of forwarders and cable skidders obtained from FMP data and field surveys, as indicated by the Wilcoxon tests, but no significant differences were found for all-terrain cable yarders. The highest correlations were found between the suitability values and the extracted timber volume ($R = 0.67$ for forwarders and $R = 0.45$ for cable skidders), while soil-bearing capacity also showed a relatively high correlation with forwarders ($R = 0.63$). However, no significant correlations were found with the variations in suitability values for the other variables. In conclusion, the results suggest that the choice of the optimal extraction system depends on several factors, including slope, extracted timber volume, and road availability. The differences between the FMP data and those collected in the field emphasize the importance of making forest management decisions based on direct assessments of the area to optimize cutting operations and improve forest management efficiency.

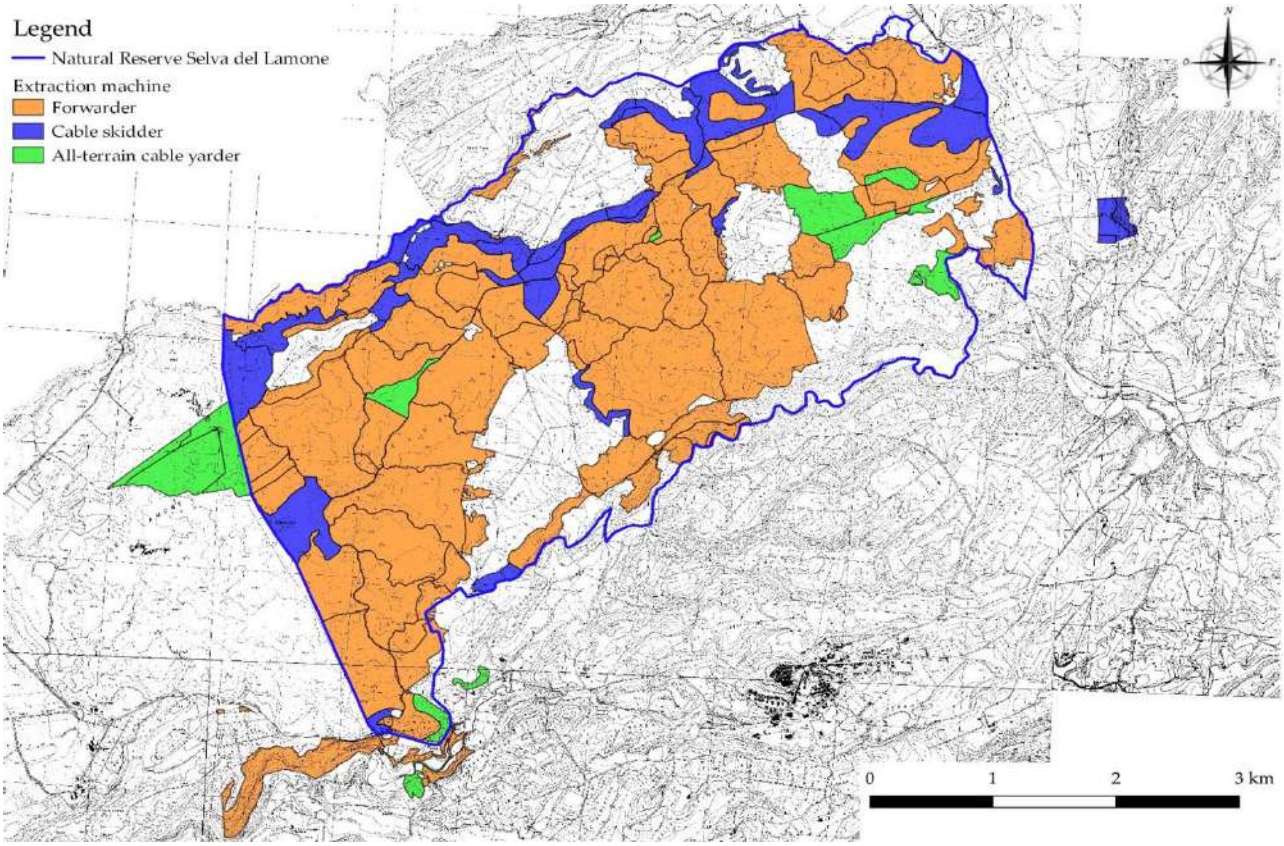

Figure 6. *Extraction system suggested by the GIS-AHP procedure in all the cutting blocks of the study area. It is important to notice that there are some cutting blocks outside the boundaries of the Natural Reserve Selva del Lamone. However, these cutting blocks, even if outside the reserve's territory, are managed by the Natural Reserve concerning forest management issues.*

Table 11. *Suggested extraction system for the investigated parcels with the output of the GIS-AHP procedure developed by the FMP data and field surveys carried out in the framework of this study. The* ***italic bold*** *indicates the cutting blocks with a different suggested extraction system between the two simulations.*

Cutting block	Field surveys	FMP
20-1	Forwarder	Forwarder
31-1	***Cable skidder***	***Forwarder***
31-3	Cable skidder	Cable skidder
33-1	***Cable skidder***	***Forwarder***
35-1	Forwarder	Forwarder
39-2	Forwarder	Forwarder
49-1	Forwarder	Forwarder
56-1	Forwarder	Forwarder
63-1	Cable skidder	Cable skidder
65-3	***Cable skidder***	***Forwarder***

Table 12. *Spearman's R and p-value for the various couple comparison between variations of suitability values for forwarder and cable skidder and variations of the six variables' values. For variation, what is meant is the difference between the values calculated from FMP data and the values retrieved after the field surveys carried out in the present study. FORW: forwarder; SKID: skidder; S: slope; ED: extraction distance; SBC: soil-bearing capacity; ETA: extracted timber amount; RG: terrain roughness.*

	Spearman's R	***p*-Value**
FORW and S	0.2236	>0.05
FORW and RG	−0.2294	>0.05
FORW and SBC	0.6309	>0.05
FORW and ETA	0.6708	>0.05
FORW and ED	−0.1118	>0.05
SKID and S	0.21622	>0.05
SKID and RG	−0.3028	>0.05
SKID and SBC	0.2644	>0.05
SKID and ED	−0.1261	>0.05
SKID and ETA	0.4505	>0.05

5.3. The third research goal result

The results of the experimental treatments analysis highlight significant differences in the physical and biological properties of the soil between areas sensitive to disturbances (identified by a DTW index ≤1) and other areas. Specifically, soil moisture in areas with DTW ≤1 was significantly higher compared to non-sensitive areas, both in plots treated with high and medium mechanization. However, regarding soil bulk density, penetration resistance, and shear resistance, no significant differences were observed between sensitive and non-sensitive areas in the high mechanization plots (HM), while slight differences were found in the MM plot (with medium mechanization), particularly in shear resistance. Regarding soil organic matter, values were not fully recovered to pre-intervention levels, with significantly lower values in disturbed areas compared to the control area. The soil biological quality index (QBS-ar) showed significantly lower values in areas with DTW ≤1, indicating a stronger biological impact in disturbance-sensitive zones.

Finally, the nMDS analysis confirmed that areas with a lower DTW index (indicating greater sensitivity to disturbance) experienced a higher level of disturbance compared to other areas, with more evident differences in the medium mechanization (MM) plot. Overall, the results suggest that while some physical soil parameters have quickly recovered, organic matter and biological quality require more time to fully recover after harvesting.

Table 13. *Soil moisture values referred to the different conditions analysed and results of the indepen- dent T-test analysis (HM-DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level).*

Treatment	Moisture %	t-Value	*p*-Value (AVG ± SD)
HM-DTW	39.6 ± 2.2	6.566	<0.001
HM	35.7 ± 1.9		
MM-DTW	40.0 ± 3.9	7.930	<0.001
MM	32.9 ± 1.9		

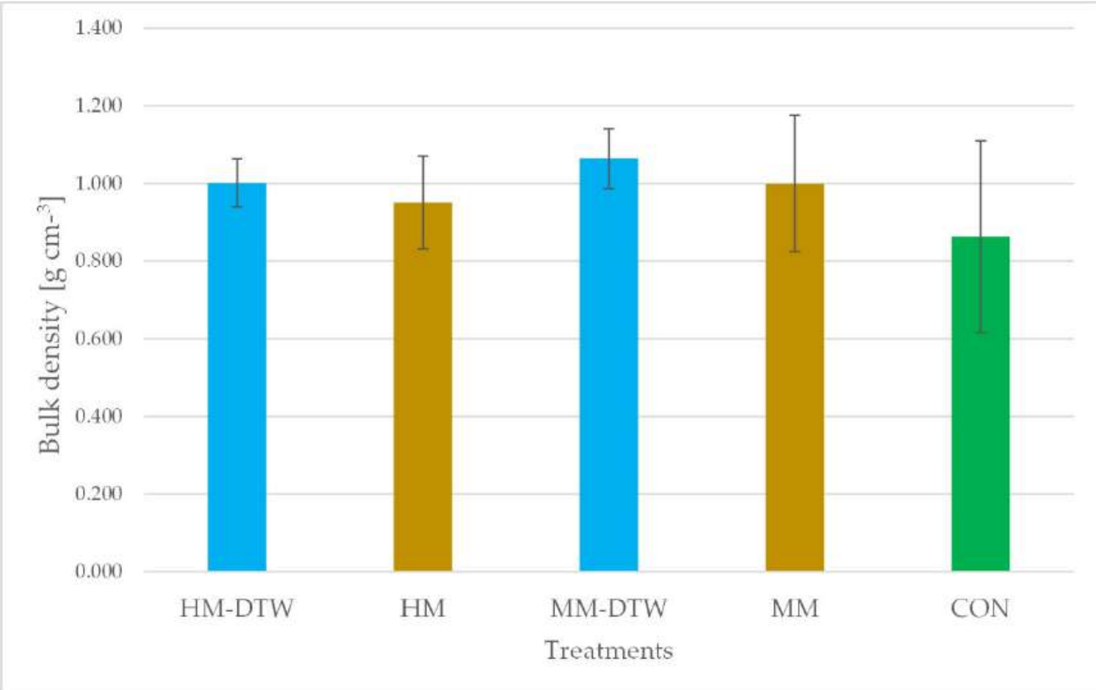

Figure 7. *Bulk density for the different treatments. Obtained p-value from ANOVA was p = 0.37 (HM- DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level; CON—control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels).*

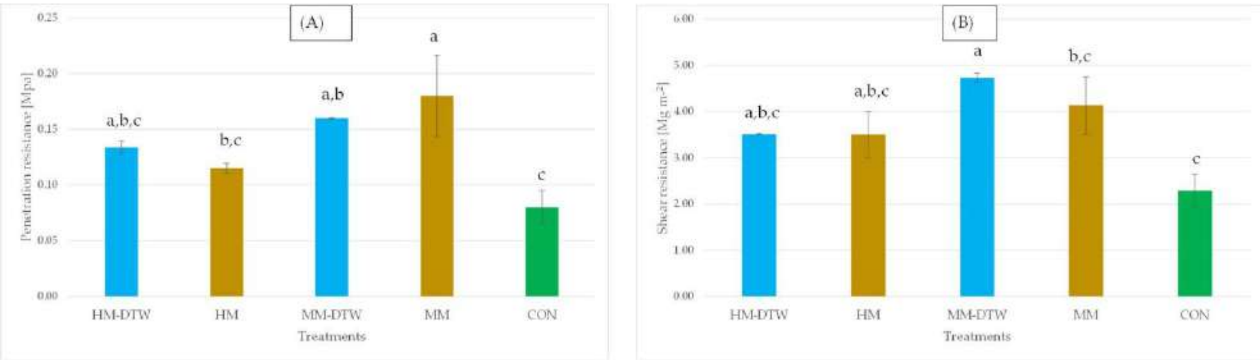

Figure 8. *Penetration resistance (**A**) and shear resistance (**B**) for the different treatments. Obtained p-values from ANOVA were p = 0.00041 for penetration resistance and p = 0.00012 for shear resistance. Different letters indicate homogeneous groups (p < 0.05) according to HSD Tukey test (HM-DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level; CON—control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels). Different lowercase letters indicate different homogeneous groups at p < 0.05 according HSD Tukey Test.*

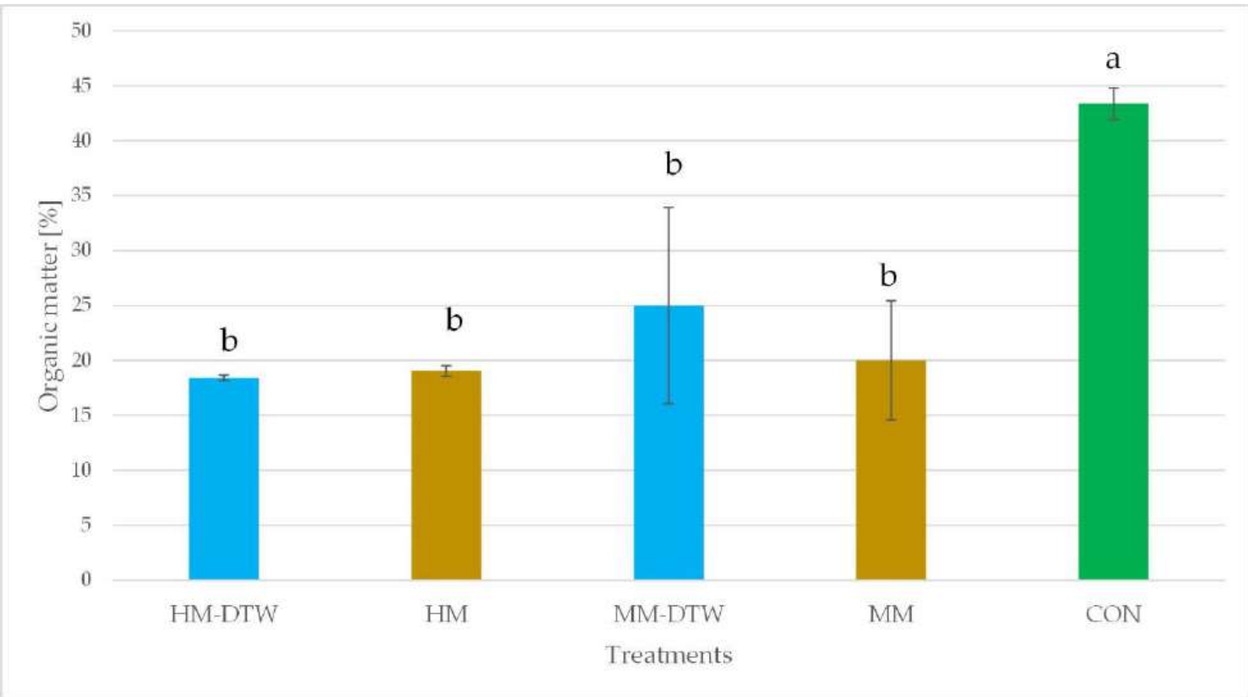

Figure 9. *Organic matter for the different treatments. Obtained p-value from ANOVA was p = 0.00001. Different letters indicate homogeneous groups (p < 0.05) according to HSD Tukey test (HM-DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level; CON—control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels. Different lowercase letters indicate different homogeneous groups at p < 0.05 according HSD Tukey Test).*

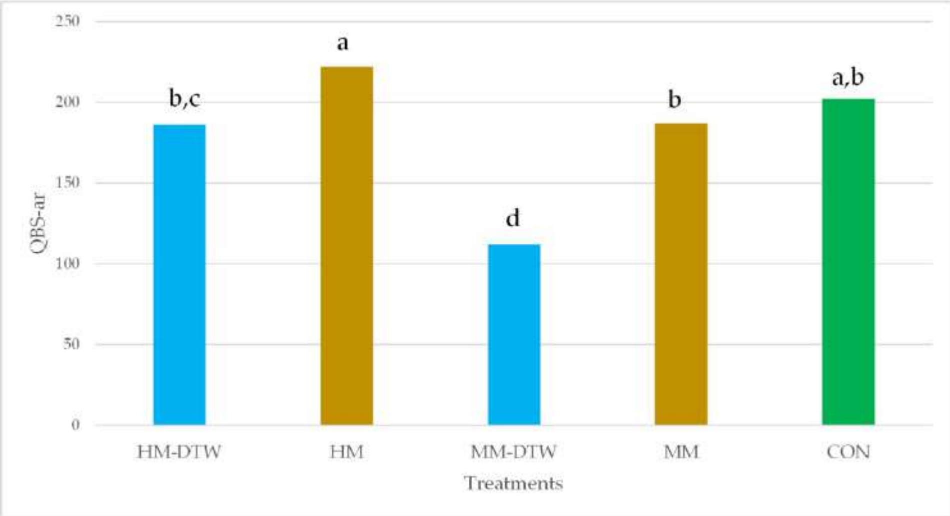

Figure 10. *QBS-ar index for different treatments. Obtained p-value from Kruskal–Wallis test was p = 0.0013. Different letters indicate homogeneous groups (p < 0.05) according to Duncan test (HM- DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level; CON—control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels). Different lowercase letters indicate different homogeneous groups at p < 0.05 according HSD Tukey Test.*

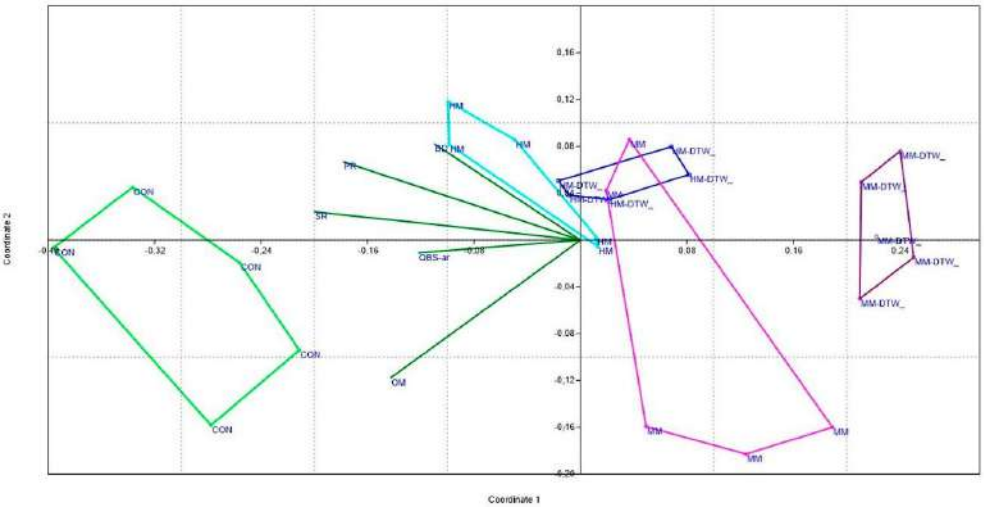

Figure 11. *Non-metric multidimensional scaling (nMDS) analysis of the main indexes and indicators of the disturbed soil and the control (BD—bulk density; PR—penetration resistance; SR—shear resistance; OM—organic matter; QBS-ar—soil biological quality based on microarthropods soil bio- logical quality) (HM-DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level; CON—control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels).*

Although the absence of a high-resolution Digital Elevation Model (DEM) may hinder an accurate assessment of soil trafficability, GIS tools still provide valuable support for the planning of extraction trails. In this context, a harvesting operation was simulated in a riparian forest in Central Italy, comparing two different extraction systems: a cable skidder and a forwarder.

At present, the cable skidder is able to access 84% of the intervention area, and with the construction of only 640 meters of new skid trails, the entire area would become accessible. However, the use of a forwarder would require a significantly more extensive road network. Given the low market value of wood chips, the use of advanced machinery is essential to ensure the economic viability of the operation. Forwarders offer high productivity but cause greater soil disturbance.

The precision forest harvesting approach proves to be highly effective in planning forest road networks, enabling operators to follow optimized routes via onboard computers, thus improving operational efficiency and safety.

Table 14: *Detailed of the planned forest road networks.*

Parameter	Cable skidder	Forwarder
Surface currently accessible (ha)	9.42	-
Surface currently accessible (%)	84	-
Adjunctive skid trails/strip roads (m)	640	5,561
Post-intervention viability density (m/ha)	172	611

6. CONCLUSIONS

The results obtained in this study fully confirm the achievement of the initial objectives and validate the effectiveness of the adopted methodological approach. In particular, the integration of the GIS-AHP methodology with soil sensitivity analyses has proven to be a robust and scientifically grounded decision-support tool, enabling more efficient, sustainable, and informed forest management planning. One of the most significant outcomes of the research concerns the optimization of harvesting system selection. The multi-criteria analysis, based on geomorphological and environmental parameters, enabled a more precise identification of the most suitable areas for specific extraction technologies. The findings indicate that cable skidders and yarders are more appropriate in areas with steep slopes or complex terrain, while forwarders are better suited to flat areas or soils with higher load-bearing capacity. This alignment between technology and site characteristics results in increased operational efficiency and reduced environmental impact, one of the study's core goals. Furthermore, the integration of analytical tools significantly reduces subjectivity in the decision-making process. The proposed approach allowed for management choices to be guided by objective, verifiable criteria, promoting a balanced consideration of ecological, economic, and social priorities. This represents a key step toward a more transparent, rational, and replicable planning model. From an environmental perspective, the use of Depth to Water (DTW) maps proved valuable for identifying areas with a high risk of soil disturbance. The collected data confirm that mechanized operations can lead to long-term soil degradation, particularly affecting organic matter and biological activity, thereby highlighting the need for mitigation measures and conservation strategies. These findings reinforce the importance of forest planning based on precautionary principles and environmental responsibility. Another important aspect that emerged is the discrepancy between theoretical data found in Forest Management Plans and field observations. These differences underline the necessity of continuous monitoring and adaptive management strategies capable of responding to real-world conditions and dynamic ecosystem processes.

In conclusion, this research successfully achieved its intended objectives, demonstrating that the integration of GIS tools, AHP methodology, and soil sensitivity assessments provides an effective model for sustainable forest resource management. The findings contribute meaningfully to both scientific discourse and practical forest planning, offering an innovative and transferable approach applicable to diverse ecological and geographic contexts. These results may serve as a valuable foundation for future studies and for the development of management strategies that balance productivity, environmental protection, and social responsibility.

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8. ATTACHEMENTS

8.1. GIS-AHP Approach in Forest Logging Planning to Apply Sustainable Forest Operations. Latterini, F., Stefanoni, W., Venanzi, R., Tocci, D., Picchio, R. - (2022) FORESTS

8.2. A Preliminary Validation and Assessment of a GIS Approach Related to Precision Forest Harvesting in Central Italy. Stefanoni, W., Tocci, D., Latterini, F., Venanzi, R., Gaglioppa, P., Pari, L., Picchio, R. - (2023) FORESTS

8.3. Depth-to-Water Maps to Identify Soil Areas That Are Potentially Sensitive to Logging Disturbance: Initial Evaluations in the Mediterranean Forest Context. Latterini, F., Venanzi, R., Tocci, D., Picchio, R. – (2022) LAND

8.4. Statistical Validation Of Gis-Ahp Systems For Forest Harvesting Planning. Pari, L., Cozzolino, L., Stefanoni, W., Simone, B., Lazar, S., Picchio, R., Latterini, F., Latterini, F. - (2023) European Biomass Conference and Exhibition Proceedings

8.5. Precision Forest Harvesting Approach In The Utilization Of Riparian Forests. Latterini, F., Stefanoni, W., Lazar, S., Pari, L., Venanzi, R., Tocci, D., Picchio, R. - (2022) European Biomass Conference and Exhibition Proceedings

8.1 GIS-AHP Approach in Forest Logging Planning to Apply Sustainable Forest Operations. Latterini, F., Stefanoni, W., Venanzi, R., Tocci, D., Picchio, R. - (2022) FORESTS

Abstract: This study represents the first attempt of integration, within a Forest Management Plan (FMP), of a Geographic Information System (GIS) and an Analytic Hierarchy Process (AHP) approach for the selection of the most suitable logging method. It is important to underline that the developed methodology is applicable worldwide in each environmental context in which there is a need for planning the intervention and selecting from among several possible logging methods or harvesting systems. Schematically, the main aims of this study were: (i) to develop a GIS-AHP method based on open-access GIS software; (ii) to compare the results of the simulations developed from the statements of two different groups of experts from around the world, to determine the reliability of the predictive probability of the method. The selection of the extraction methods performed with RTS (experts from research and technical sector) input data showed that the most suitable option in the major part of the study area was the cable skidder, followed by the cable yarder, and finally the forwarder. The extraction system selection performed with OS (people from the operative sector) input data revealed limited differences. Thus, considering what was reported above, it is possible to assert that the applied GIS-AHP methodology showed good performance and high consistency in the selection of the best alternatives among different extraction methods. The idea of comparing the results obtained from a survey based on a pool of researchers and forest engineers (RTS) was taken as a target simulation to be evaluated. The method based on data derived from a pool of expert forest operators (OS) was used to check for the results of the other simulation. This is an innovation in these kinds of studies. The results from the consistency check were encouraging, considering that for 51 sub-compartments, only two changed the selected extraction system between RTS and OS.

Keywords: sustainable forest management; precision forestry; MCDA; precision forest harvesting *forests*

Article

GIS-AHP Approach in Forest Logging Planning to Apply Sustainable Forest Operations

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Abstract: This study represents the first attempt of integration, within a Forest Management Plan (FMP), of a Geographic Information System (GIS) and an Analytic Hierarchy Process (AHP) approach for the selection of the most suitable logging method. It is important to underline that the developed methodology is applicable worldwide in each environmental context in which there is a need for planning the intervention and selecting from among several possible logging methods or harvesting systems. Schematically, the main aims of this study were: (i) to develop a GIS-AHP method based on open-access GIS software; (ii) to compare the results of the simulations developed from the statements of two different groups of experts from around the world, to determine the reliability of the predictive probability of the method. The selection of the extraction methods performed with RTS (experts from research and technical sector) input data showed that the most suitable option in the major part of the study area was the cable skidder, followed by the cable yarder, and finally the forwarder. The extraction system selection performed with OS (people from the operative sector) input data revealed limited differences. Thus, considering what was reported above, it is possible to assert that the applied GIS-AHP methodology showed good performance and high consistency in the selection of the best alternatives among different extraction methods. The idea of comparing the results obtained from a survey based on a pool of researchers and forest engineers (RTS) was taken as a target simulation to be evaluated. The method based on data derived from a pool of expert forest operators (OS) was used to check for the results of the other simulation. This is an innovation in these kinds of studies. The results from the consistency check were encouraging, considering that for 51 sub-compartments, only two changed the selected extraction system between RTS and OS.

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Citation: Latterini, F.; Stefanoni, W.; Venanzi, R.; Tocci, D.; Picchio, R. GIS-AHP Approach in Forest Logging Planning to Apply Sustainable Forest Operations. *Forests* **2022**, *13*, 484. https://doi.org/10.3390/f13030484

Academic Editor: Kalle Kärhä

Received: 23 February 2022
Accepted: 18 March 2022
Published: 21 March 2022

1. Introduction

Land use and land management are key topics in the international debates for environmental policies which take into account the protection of the environment and the public demand for forest products [1]. Furthermore, the growing public awareness on sustainable exploitation of the natural resources is fostering the expectation on scholars and forest engineers for a better management of such resources. This implies a broader view on the possible critical aspects related to the forest management sector [2].

The key instrument for forest management is the Forest Management Plan (FMP), which consists of a recommended action plan for a given medium-large forest area [3]. The usual time span is in the range between 5 and 20 years.

Typically, the FMP should schedule multiple aspects related to environmental and forest management, encompassing several activities which stretch from silviculture to road construction, also including forest logging [4]. Currently, forest planning should meet the goal of Sustainable Forest Management (SFM); therefore, FMP should be addressed to develop a management which safeguards each of the three pillars of sustainability (economy, society and environment) [5–7]. A proper planning of the forest activities is a crucial issue in the context of SFM [8,9].

Among the several aspects which a modern FMP should thus include, a key role is related to the proper planning of the harvesting activities by implementing Sustainable Forest Operations (SFOs) and following best practices as Reduced Impact Logging (RIL) approaches [10,11]. The SFO concept consists of the implementation of harvesting operations which allow for high work productivity (i.e., low costs), low environmental impacts and safe working conditions for the operators [12]. According to the above, identifying the most suitable harvesting system in forest operations is a challenging but crucial issue [13–15]. Several aspects have some influence on the decision regarding the harvesting system to be applied in a given forest intervention, and among them, there are stand and terrain characteristics, management goals, accessible technology, and forest infrastructure [16]. Multi Criteria Decision Analysis (MCDA) is a group of several methods which were developed to enable the analysis of situations based on decisions that require multiple criteria [3]. MCDA is usually applied to deal with planning situations in which there is the need to holistically evaluate different decision alternatives [17,18]. Several MCDA methods can be applied in natural resources management, but among them, the Analytic Hierarchy Process (AHP) [19] has been the most applied in the forest management sector [14]. The AHP method allows for the decomposition of a complex problem into a hierarchy, where the goal is at the top level, while criteria and alternatives are the lower levels. This method determines the preferences among several alternatives by applying a pairwise comparison of the elements [14]. The potential of AHP is even higher when it is applied along with technologies related to the Precision Forest Harvesting approach [20]. In particular, the combined application of GIS (Geographic Information System) and AHP has been found to be an interesting way to deal with the issue of managing forest resources from an objective approach [16,21,22].

However, there are still two major concerns regarding such methodology in the planning of logging activities. The first one is related to the scarce practical application of this methodology, mostly related to the "lack of interaction" between researchers and technicians, an aspect which is rather common in the forestry sector [23].

Apart from some exceptions [24], the application of such methods in the operational part of FMPs is still far from a practical implementation. Moreover, in some cases, the forest harvesting planning and related forest operations, in particular concerning bunching and extraction, is practically absent from the FMP, and the decision regarding the harvesting system is often postponed to the moment of the implementation of the intervention. This is particularly true for the Mediterranean forest sector, which is mostly based on the system of selling the standing timber [25].

The second aspect which still represents an issue to be tackled in scientific studies dealing with the GIS-AHP approach to forest harvesting planning is the objective difficulty in the evaluation of the results of the prediction. In studies related to the GIS-AHP approach in natural resources management, checking for the consistency of the results can be performed in different ways, such as sensitivity analysis [26], field surveys [27] and remote sensing [28]. Currently, sensitivity analysis is a reliable and widely accepted tool, although it represents another simulation. Therefore, it is difficult to evaluate the results of the prediction of the best harvesting system in a given situation. The base idea of comparing the results of the simulation with the harvesting system which will be actually selected for the implementation of the forest yard could not be a reliable solution for checking the consistency of the predictions. Therefore, there is usually no proof that the harvesting system actually applied is the best option in that specific context.

According to what is written above, this study represents the first attempt of integration within an FMP of a GIS-AHP approach for the selection planning of the best logging method for each sub-compartment of the study area, while trying to tackle the issues reported above.

In particular, the need to expand the practical application of this approach has encouraged authors to develop a methodology to provide the forest engineers with a user-friendly tool which is based on the usage of open-source software and medium-sized hardware. Although the accuracy of open-source GIS software has already been stated [29], only a few operations have relied on it for forest logging applications [9,30,31]. It is important to underline that the developed methodology should be applicable worldwide in each environmental context in which there is the need for planning the intervention by selecting from among several possible logging methods or harvesting systems.

In summary, the objectives of this study were: (i) to develop a GIS-AHP method based on open-access GIS software which allows for the selection of the most suitable option among different extraction methods for forest operations in a mountainous context, while keeping in consideration the parameters of the pillars of sustainability; (ii) to compare the results of the simulations developed from the statements of two different groups of experts from around the world, to determine the reliability of the predictive probability of the method.

2. Materials and Methods

2.1. Study Area and Definition of the Extraction Systems to Be Taken into Consideration

The study area corresponds to the private forest estate of Macchia Faggeta Company, located in the region of Tuscany in Italy. The overall surface of the estate covers 565 ha and is subdivided into 65 sub-compartments. The most represented species is beech (*Fagus sylvatica* L.), but there are also some silver fir (*Abies alba* Mill.), Douglas-fir (*Pseudotsuga menziesii* Mirb.), black pine (*Pinus nigra* Arn.), and Norway spruce (*Picea abies* (L.) Karst) artificial plantations. Beech forest represents 98% of the study area, while overall softwood stands comprise the remaining 2%.

The forest stand, both softwood and hardwood, in the study area are for the greater part even-aged high stand, and the applied silviculture treatment is the shelterwood system. It is important to mention that there is a permanent no-intervention area named the wild area. This zone consists of high stands of beech which are deliberately designed as permanent no-intervention areas by the *Macchia Faggeta* forest managers so as to allow for the natural development of the zone. It is also important to mark that the identification of the most suitable extraction method was carried out for only 51 sub-compartments, excluding the twelve parcels belonging to the wild area and two other small sub-compartments. The surface area in which the extraction system selection was simulated measured 449.91 ha.

Concerning road types involved in the analysis, secondary roads for trucks, skid roads, and permanent skid trails were taken into consideration to build the forest road network. Public main roads (i.e., roads used for the normal traffic of cars) were not included in the forest road network, considering that these roads cannot be used for logging activities according to Italian laws.

A view of the study area boundaries, forest typologies, and forest road network is given in Figure 1.

The study area is located in a Mediterranean mountainous context, and as previously stated, the major part of the surface consists of hardwood stands managed with the shelterwood system. Taking into account these aspects, the authors considered only motor-manual felling and processing by chainsaw, a common choice in hardwood stands mostly used in the Mediterranean areas [32]. The analysis was therefore focused on different extraction methods which are suitable to a mountainous context. These methods are currently applied or have potential to be introduced into practice in this and similar contexts. We took into consideration two ground-based extraction systems (i.e., forwarder and cable skidder) and one aerial extraction system (medium cable yarder). Previous studies have demonstrated the suitability of these systems in extraction operations in similar working conditions [9,30,31].

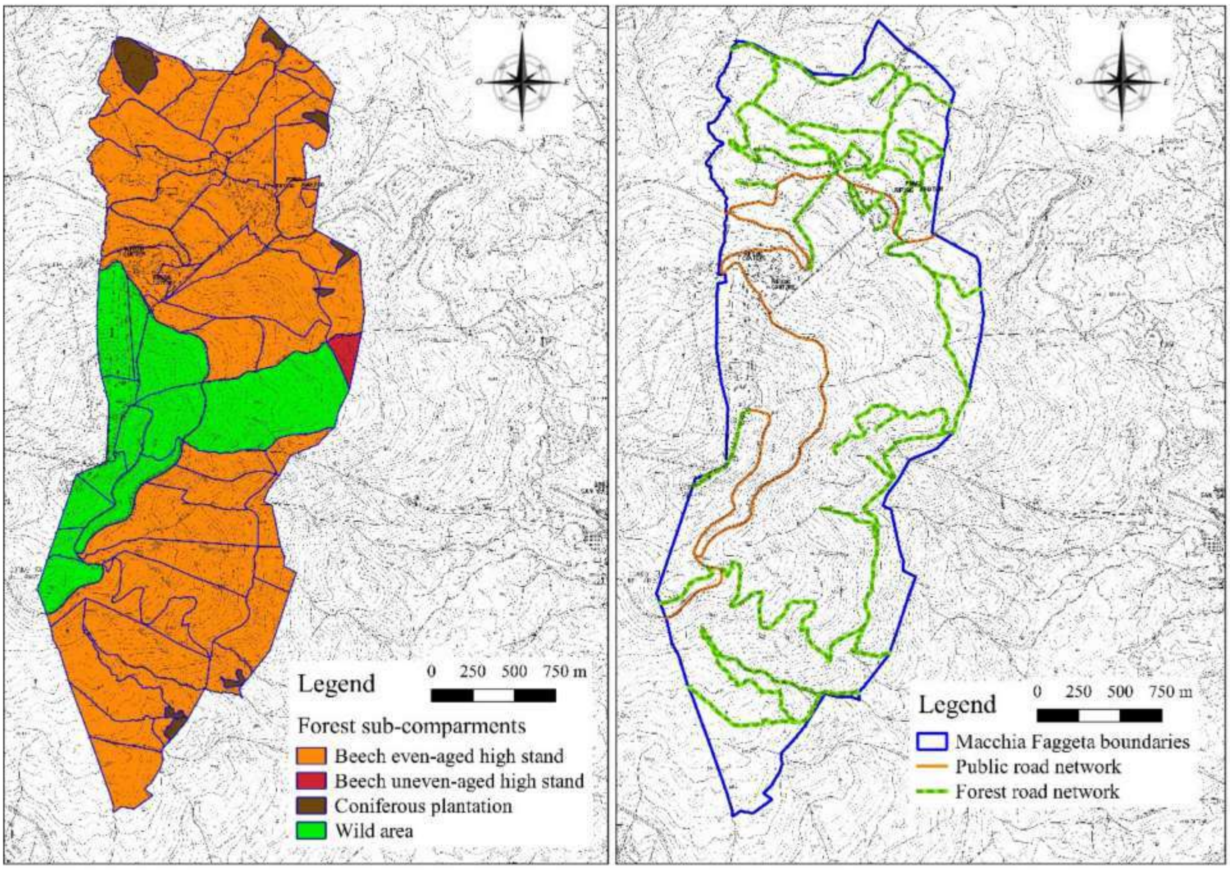

Figure 1. On the left, the subdivision into forest typologies of the study area. On the right, Macchia Faggeta boundaries and road network on a technical map of the Tuscany Region.

2.2. Literature Review of Criteria Selection

Selecting the most suitable extraction method in forest operations is a complex task, as there are several parameters which contribute to making a specific system suitable or not in a given context. The different types of variables to be taken into account for the proper selection of the extraction method should be related to the topographical features of the intervention area, to the applied silvicultural treatment, to the forest infrastructures which are present (i.e., roads, landing sites, etc.) and to the characteristics of the forest stand. A literature review of scientific papers in the topic of harvesting operations identified six different criteria which were considered for the analysis carried out in the present work. In particular, the authors considered: slope, extraction distance, soil bearing capacity, extracted timber amount, road density, and roughness. The summary of the various criteria, with the specification of the aspects of sustainability (economy, environment and society) in which they have their influence, is given in Table 1.

Terrain slope is one of the most important parameters to be taken into consideration when planning forest intervention [33–36]. As a general rule, ground-based extraction systems perform better in lower slope, while cable yarders in steeper terrains [16]. As reported in Table 1, however, slope not only affects work productivity but also the environment and social aspects. Regarding the environment, previous studies have shown that logging in steep slope via ground-based systems led to higher soil compaction and reduced growth of seedlings [37,38]. Focusing instead on worker safety, it is important to underline the fact that applying ground-based extraction in terrains with excessive slope could increase risks of accident during the movement of the machineries [9].

Table 1. Identified criteria for the selection of the most suitable harvesting system with reference to the various pillars of sustainability.

Criterion	Acronym	Economy	Environment	Society
Slope (%)	S	✓	✓	✓
Extraction Distance (m)	ED	✓	✓	✓
Soil Bearing Capacity (kPa)	SBC	✓	✓	✓
Extracted Timber Amount (m^3 ha^{-1})	ETA	✓		
Road Density (m ha^{-1})	RD	✓	✓	✓
Roughness (%)	RG	✓		✓

Extraction distance is defined as the distance between the logs to be extracted and the nearest forest road [39]. Several studies have focused on the analysis of the influence of extraction distance on work productivity, revealing the strong influence of this parameter on the cost effectiveness of forest interventions [40–42]. In this case however, the implications of such a criterion on the sustainability of the intervention is not limited only to economic aspects, considering dealing with ground-based extraction or aerial extraction with logs in partial suspension, a higher extraction distance implies a higher level of disturbance to soil [43,44] and harsher working conditions for the operators [30]. Similar considerations can be made regarding road density, which is defined as the ratio between the length of the forest roads usable for timber extraction from one forest parcel and the surface of the same parcel [45,46]. High road density is generally related to higher work productivity, mostly dealing with ground-based extraction systems [47]. Conversely, the presence of a proper road density is related to safer working conditions for the operators [9], while focusing on the environmental aspects, an increase in this parameter has been considered as an indicator of the magnitude of disturbance triggered by forest operations of soil [9,30].

Soil bearing capacity is another key factor in the selection of a proper extraction system [16]. The lower value of soil bearing capacity limits the possibility of the application of ground-based extraction systems, increasing the impacts on forest soil, decreasing work productivity, and enhancing the risks of accidents [48–51].

Roughness is another parameter which has a strong influence on ground-based extraction, and it is recognized as one of the most important limiting factors regarding forest operations in mountainous contexts [52,53]. High roughness limits the movement of forestry machines, decreasing work productivity, and it could lead to a higher level of accident risk.

Finally, another criterion to be taken into consideration when planning forest operations is the extractable timber amount. This variable is mainly related to the cost-effectiveness of the logging activity. As a general rule, the higher the extracted volume the higher the work productivity [16,54].

2.3. Data Collection and Criteria Scoring

After the identification of the criteria for the selection of the extraction method, it was needed to obtain data regarding each criterion for the study area to set up the GIS-AHP methodology and to identify the best alternative for each forest sub-compartment. The GIS software applied for the required analysis was the open-source Quantum GIS ver. 3.16. A personal computer with processor Intel Core i5 2.20 GHz, a graphics processing unit (GPU) NVIDIA GeForge310, and 8.0 Gb RAM was used for the study. The minimum system and hardware requirements for the software are: Core i3 2.7 GHz Processor, 1 Gb Graphic card, 2 Gb Memory RAM, and Windows 7–10 OS [55].

Slope map for the study area was developed starting from a free regional DTM (Digital terrain Model) at 10 m resolution downloaded from the regional geographic data website [56]. Data regarding the forest road network, the details of the estimated extracted timber amount (derived from the forest inventory at the base of the FMP) and the roughness of each sub-compartment were derived from the Forest Management Plan of

Macchia Faggeta. Starting from the vector file of the forest road network, it was possible to calculate the extraction distance as a topographic distance applying the RDBM (Real Distance Buffer Method) developed and successfully tested in previous research [30,31].

Finally, data regarding soil bearing capacity were obtained through specific field survey. The field data were collected in spring 2020 from 600 sampling plots (about one for hectare) randomly selected on each hectare of the study area. The location of each plot was determined using a high precision GPS device, and starting from the sample plot centre, three sampling points were selected, one fifty meters away moving up along the maximum slope, and two 50 m away from the centre moving down along the maximum slope but shifted 45° to the right and left. In every sampling point, stiffness and bearing capacity were measured using a portable light falling weight deflectometer (FWD). The FWD was used to evaluate the physical properties of the soil [57,58]; the FWD used was a TERRATEST® 4000 (standard ASTM E2835-11, accelerometer with fix falling height, stress 7.07 kN, falling weights 10 kg and load plate diameter 300 mm). The values of the obtained data were then used to derive descriptive mean values of each individual particle. The map of terrain roughness was consequently developed through interpolation via TIN (Triangular Interpolation Network) method.

The above-mentioned data collection was used to obtain a raster map for each criterion in the study area. The maps for each criterion in the study area are reported in the supplementary materials (Figures S1–S6).

The following step consisted of subdividing the values of each criterion into five score classes according to the suitability of a given extraction system. To do this, the various maps of the criteria were reclassified according to the suitability criteria score classes reported in Table 2. The definition of the various scores was performed according to the literature data [14,59] and taking into account the values of the various criteria in the study area, considering what was stated in the previous sections of this manuscript. The higher the score, the higher the suitability of the extraction system in that particular condition of value of the criterion.

Table 2. Suitability criteria classes for the different investigated extraction systems.

Extraction System	Criteria											
	Slope		Extraction Distance		Soil Bearing Capacity		Extracted Timber Amount		Road Density		Roughness	
	Range (%)	Score	Range (m)	Score	Range (kPa)	Score	Range (m^3 ha^{-1})	Score	Range (m ha^{-1})	Score	Range (%)	Score
Forwarder	0–20	5	0-100	5	>80	5	>200	5	>207	5	0–15	5
	20–40	4	100–200	5	60–80	4	100–200	4	138–207	4	15–30	4
	40–60	1	200–400	4	40–60	2	80–100	3	69–138	3	30–45	1
	>60	0	>400	1	<40	0	<80	1	<69	1	>45	0
Cable Skidder	0–20	5	0-100	5	>80	5	>200	5	>207	5	0–15	5
	20–40	5	100–200	1	60–80	5	100–200	5	138–207	5	15–30	5
	40–60	4	200–400	0	40–60	3	80–100	4	69–138	4	30–45	4
	>60	2	>400	0	<40	1	<80	3	<69	2	>45	3
Medium gravity Cable Yarder	0–20	0	0–100	1	>80	5	>200	5	>207	5	0–15	5
	20–40	4	100–200	3	60–80	5	100–200	5	138–207	5	15–30	5
	40–60	5	200–400	5	40–60	5	80–100	4	69–138	4	30–45	5
	>60	5	>400	5	<40	3	<80	1	<69	3	>45	4

2.4. AHP Methodology and Expert Survey

The Analytic Hierarchy Process (AHP) is a complex decision-making tool which takes into account the priorities of each of the selected criterion [19]. For this purpose, AHP establishes an importance rank ranging from 1 to 9 (1 = equal importance, 3 = weak dominance, 5 = strong dominance, 7 = demonstrated dominance, 9 = absolute dominance; even values refer to intermediate choices) [14]. This scale allows the decision makers to make comparisons among different units within a hierarchy. AHP converts the preference values to a numerical scale in order to evaluate together the different criteria. The AHP provides users with a tool to compare and specify the importance of any criterion to another by the development of a pairwise comparison matrix. AHP assigns an importance value (weight) to each criterion, Wi (i = 1, 2, 3, . . . , n), through given preference values and pairwise comparisons. Moreover, the AHP provides a consistency rate concept to evaluate the consistency of the different weights and priorities. The consistency ratio (CR) should be less than 0.1 in order to have consistency between weights and priorities.

In order to have reliable data for AHP, a questionnaire was developed and distributed to forest experts from around the world. The questionnaire was developed in a way that answers were classified in accordance with the Saaty scale [60].

In particular, 300 requests of compilation were sent to senior forest researchers and expert forest engineers. The contact details for sending the requests were taken from the main database for international cooperation regarding forest projects. Forest experts from 65 countries were invited to complete the survey. In this way, the input data were obtained for AHP from a pool of forest operations experts from the research and technical sector of forestry (RTS). The authors received 119 replies out of the 300 requests sent.

Subsequently, the authors asked people who answered the survey to indicate the contacts of skilled and expert forest operators. The survey was then sent to 120 forest operators from 32 different countries, obtaining 59 answers. Thus, a second set of input data for AHP was obtained relying on the expertise of people from the operative sector of forestry (OS). This second set of data was used to check for the consistency of the results of the GIS-AHP procedure developed with RTS data. The base idea was that the higher the consistency between the two simulations (RTS and OS), the higher the probability that the individuated extraction system was actually the most suitable in the given forest sub-compartment.

The nationalities of those who replied for both RTS and OS is reported in Table 3. The most represented countries for RTS were Italy, Croatia and the United States of America. For OS the most represented nations were Italy, Canada and the USA.

Table 3. Details of the survey.

Country	RTS		OS	
	Asked	Respondents	Asked	Respondents
Albany	7	3	1	1
Argentina	7	3	1	1
Australia	8	4	2	2
Austria	8	4	2	0
Brazil	12	2	3	1
Canada	12	4	6	4
Cameroon	7	3	3	1
Chile	6	2	2	0
China	7	3	2	0
Congo	8	4	4	0
Croatia	15	8	7	3

Table 3. *Cont.*

Country	RTS		OS	
	Asked	**Respondents**	**Asked**	**Respondents**
Czech Republic	7	3	5	3
United Kingdom	15	6	4	2
France	7	3	5	3
Germany	9	5	5	3
Greece	6	2	2	0
India	5	1	2	0
Iran	6	2	1	1
Italy	29	17	15	10
Japan	7	3	3	1
New Zealand	9	5	4	2
Poland	12	2	3	1
Romania	14	1	4	2
Russia	8	4	4	2
Slovenia	8	4	4	2
South Africa	7	3	4	2
Spain	15	3	5	3
Sweden	9	3	3	2
Switzerland	7	3	3	1
Turkey	8	2	3	1
Uganda	6	2	2	0
USA	9	5	5	5
Total	300	119	119	59

It is important to underline the fact that the high number of replies from all over the world represents a key aspect in the present work, considering that previous similar studies were performed relying on surveys carried out with a local approach and with a low number of replies, ranging from 1 to 17 [16,17,61,62].

2.5. Development of the Suitability Maps for the Various Extraction Systems and Definition of the Best Alternative for Each Sub-Compartment

Subsequently, an AHP pairwise comparison matrix was developed for both RTS and OS in order to determine the weights of each criterion for each of the three extraction systems; to perform the calculation, the dedicated tool of Quantum GIS was applied [63]. CR value was calculated as well to check for the consistency of the weights. The various pairwise comparison matrices for the various extraction systems in both RTS and OS are given in Table 4.

The overall suitability of each extraction system for each pixel of the study area was calculated with the map algebra approach via the raster calculator of Quantum GIS. In detail, a weighted average function was applied for each extraction system multiplying the score of the criteria for its related weight, derived from the AHP pairwise comparison matrix. The suitability map of each extraction system was further reclassified into 10 classes [64].

Table 4. AHP pairwise comparison matrices.

	Criteria	S	ED	SBC	ETA	RD	RG	weights	CR
RTS	Forwarder								
	Criteria	S	ED	SBC	ETA	RD	RG	weights	CR
	S	1	1	0.5	1	1	1	0.143	0.0001
	ED	-	1	0.5	1	1	1	0.143	
	SBC	-	-	1	2	2	2	0.286	
	ETA	-	-	-	1	1	1	0.143	
	RD	-	-	-	-	1	1	0.143	
	RG	-	-	-	-	-	1	0.143	
	Cable Skidder								
	Criteria	S	ED	SBC	ETA	RD	RG	weights	CR
	S	1	0.5	1	2	0.5	1	0.136	0.002
	ED	-	1	2	3	1	2	0.259	
	SBC	-	-	1	2	0.5	1	0.136	
	ETA	-	-	-	1	0.3333	0.5	0.075	
	RD	-	-	-	-	1	2	0.259	
	RG	-	-	-	-	-	1	0.136	
	Medium Gravity Cable Yarder								
	Criteria	S	ED	SBC	ETA	RD	RG	weights	CR
	S	1	1	3	0.3333	1	3	0.161	0.01
	ED	-	1	3	0.3333	1	3	0.161	
	SBC	-	-	1	0.2	0.3333	1	0.06	
	ETA	-	-	-	1	3	5	0.399	
	RD	-	-	-	-	1	3	0.161	
	RG	-	-	-	-	-	1	0.06	
OS	Forwarder								
	Criteria	S	ED	SBC	ETA	RD	RG	weights	CR
	S	1	1	0.5	1	2	2	0.171	0.003
	ED	-	1	0.5	1	2	2	0.171	
	SBC	-	-	1	2	3	3	0.31	
	ETA	-	-	-	1	2	2	0.171	
	RD	-	-	-	-	1	1	0.089	
	RG	-	-	-	-	-	1	0.089	
	Cable Skidder								
	Criteria	S	ED	SBC	ETA	RD	RG	weights	CR
	S	1	0.5	1	2	1	1	0.155	0.001
	ED	-	1	2	3	2	2	0.297	
	SBC	-	-	1	2	1	1	0.155	
	ETA	-	-	-	1	0.5	0.5	0.082	
	RD	-	-	-	-	1	1	0.155	
	RG	-	-	-	-	-	1	0.155	
	Medium Gravity Cable Yarder								
	Criteria	S	ED	SBC	ETA	RD	RG	weights	CR
	S	1	0.25	1	0.14	0.5	0.5	0.054	0.012
	ED	-	1	4	0.3333	3	3	0.228	
	SBC	-	-	1	0.14	0.5	0.5	0.054	
	ETA	-	-	-	1	5	5	0.47	
	RD	-	-	-	-	1	1	0.097	
	RG	-	-	-	-	-	1	0.097	

The overlapping between the vector file of the various sub-compartments of the study area and the suitability maps for each extraction system, performed with the raster statistic tool, allowed for the identification of the most suitable extraction system for each sub-compartment. The raster suitability maps were sampled with the vector file of the sub-compartment, extracting the median value of each suitability map within each sub-compartment. The best alternative for extraction was identified as the system in each forest parcel which showed the highest median value of suitability in the specific sub-compartment. In the case of equal values between two extraction systems, the selection was carried out with forwarder as the best alternative, followed by cable skidder, and leaving cable yarder as a final option. This assertion was developed considering the fact that, when it is possible to choose, forest engineers and operators are generally prone to favour ground-based extraction rather than aerial [52,65,66]. The procedure was applied two times, one with input data from RTS and one from OS to allow for comparisons of the results. In particular, RTS was considered as the target simulation while OS was taken as a comparison to check the consistency of RTS results.

2.6. Statistical Analysis

Statistical analysis was carried out via Statistica 7.0 software. Spearman's rank correlation coefficient was calculated to identify the criteria which had the highest influence on the selection of a given extraction system regarding the RTS simulation. Paired samples t test was instead applied to evaluate the presence of statistically significant differences between the extraction systems selected in the various sub-compartments with RTS and OS.

3. Results and Discussions

Recently, several new policies and strategies have been observed in forestry, mainly related to the growing interest in sustainability due to the importance of forests as an environmental and social value [67]. Cutting-edge technology and electronic devices are potentially powerful instruments to use towards this goal. As confirmed in other studies [9,20,30,31,39,55], precision forestry, GNSS, and GIS are useful technologies for forest operations and could help to improve and optimize SFM. However, it is not always easy to apply objectively shared criteria and choices in the planning and design phase and then in the executive one.

Suitability maps, which are the base for the proposed GIS-AHP methodology, represent an interesting tool in this optic [16], giving the possibility to the forest manager to identify the zones where a given harvesting system can be applied.

The suitability maps for forwarder calculated with RTS and OS input data are reported in Figure 2a,b, respectively. As it is possible to notice, only little differences are present between the two simulations. The main difference regards the northeast part of the study area, where there is a zone in which the forwarder reached the top level of suitability, i.e., score 10, for OR, while for RTS, the score was 9. In both cases, the highest level of suitability for the forwarder was reported in the northern and southern parts of the study area, where there is the presence of soils with high bearing capacity (Figure S6).

The suitability maps developed for the cable skidder are reported in Figure 3. There are not evident differences between the RTS and OS results. In both cases, cable skidder is recommended mostly in the zones with high road density and low extraction distance. Comparing the suitability maps for the cable skidder to the ones related to the forwarder shows further evidence on how the cable skidder results were able to reach the highest score of suitability (10) in a substantially major portion of the study area.

Finally, the suitability maps for the cable yarder are reported in Figure 4. For both RTS and OS, this system reached a high level of suitability in the zones with higher extracted timber amount and/or low road density. These results confirm what is reported in the current literature, which indicates this system as the most suitable in the case of low presence of roads, and is strongly related, in the optic of cost effectiveness, to the magnitude of the harvesting intervention [34,68]. A major difference which is possible to notice while analysing the suitability maps for the cable yarder in comparison to the ones for the forwarder is the high variability of suitability scores within the study area. The forwarder reached a minimum score of 5 but a maximum of only 9, while instead for cable yarder, there are zones that are highly unsuitable (score 3) but also areas that are highly suitable (score 10). In a few words, it seems that in the study area, the forwarder can be applied in the great major part of the study area, but without being nowhere in its perfect conditions of applicability. Conversely, the cable yarder cannot be applied to a large amount of the study area, but there are zones in which it is in perfect condition for its successful application.

Starting from the overlaying of the various suitability maps, the extraction method selection performed with RTS input data showed that the most suitable extraction method in the major part of the study area was the cable skidder. According to this simulation, 54.34% of the Macchia Faggeta surface indicated the cable skidder as the best option for timber extraction. This percentage of surface corresponds to 27 sub-compartments for an overall surface of 244.49 ha. The cable yarder was selected as the best alternative in 26.67% of the surface, corresponding to 10 sub-compartments for a whole surface of 119.98 ha. Finally, the forwarder was selected in 14 sub-compartments, equivalent to 85.43 ha (18.99% of the surface).

The extraction system selection performed with OS input data revealed limited differences. In detail, the cable skidder was selected as the most suitable option in the major part of the surface in this case. This ground-based extraction system was indicated as the best alternative in 26 sub-compartments, which corresponded to 230.27 ha and 51.18% of the planned surface. Both the forwarder and cable yarder showed a slightly higher suitability when compared to the RTS results. The cable yarder was selected in 11 sub-compartments (131.73 ha and 29.28% of the surface), with the forwarder in 14 sub-compartments, corresponding to 87.91 ha and 19.54% of the surface.

The graphic representation of the extraction system selection carried out with RTS (left side) and OS (right side) is given in Figure 5.

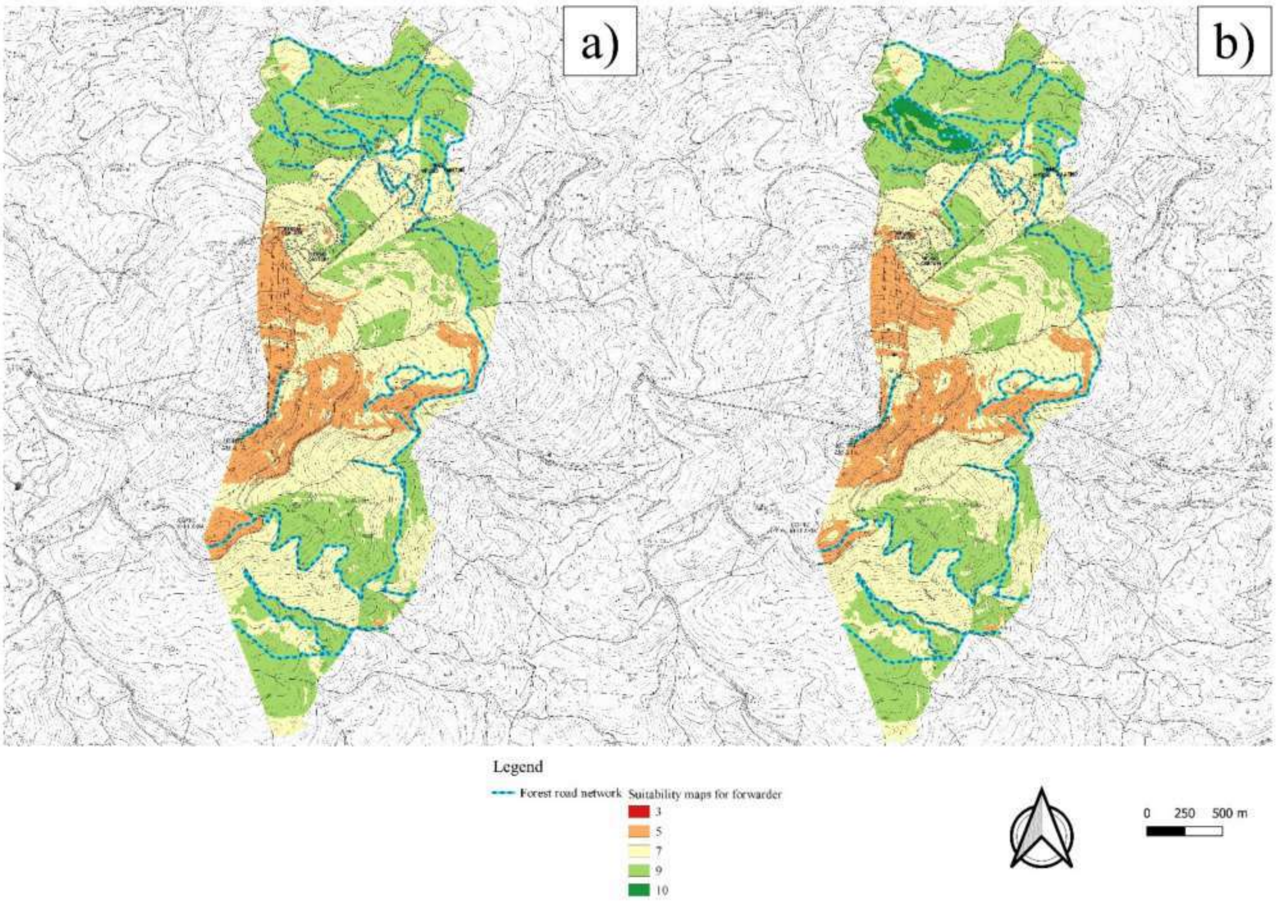

Figure 2. (**a**) Suitability map for forwarder, derived from the analysis with RTS input data. (**b**) Suitability map for forwarder, derived from the analysis with OS input data.

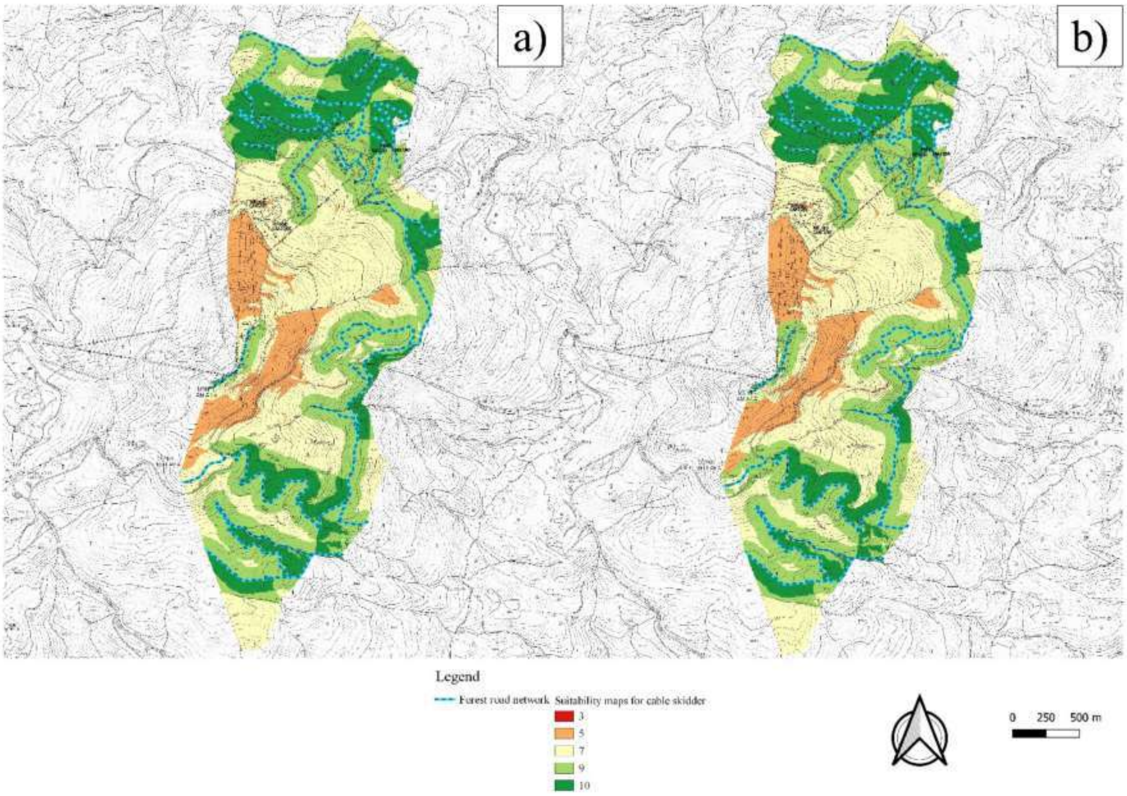

Figure 3. (**a**) Suitability map for forwarder, derived from the analysis with RTS input data. (**b**) Suitability map for forwarder, derived from the analysis with OS input data.

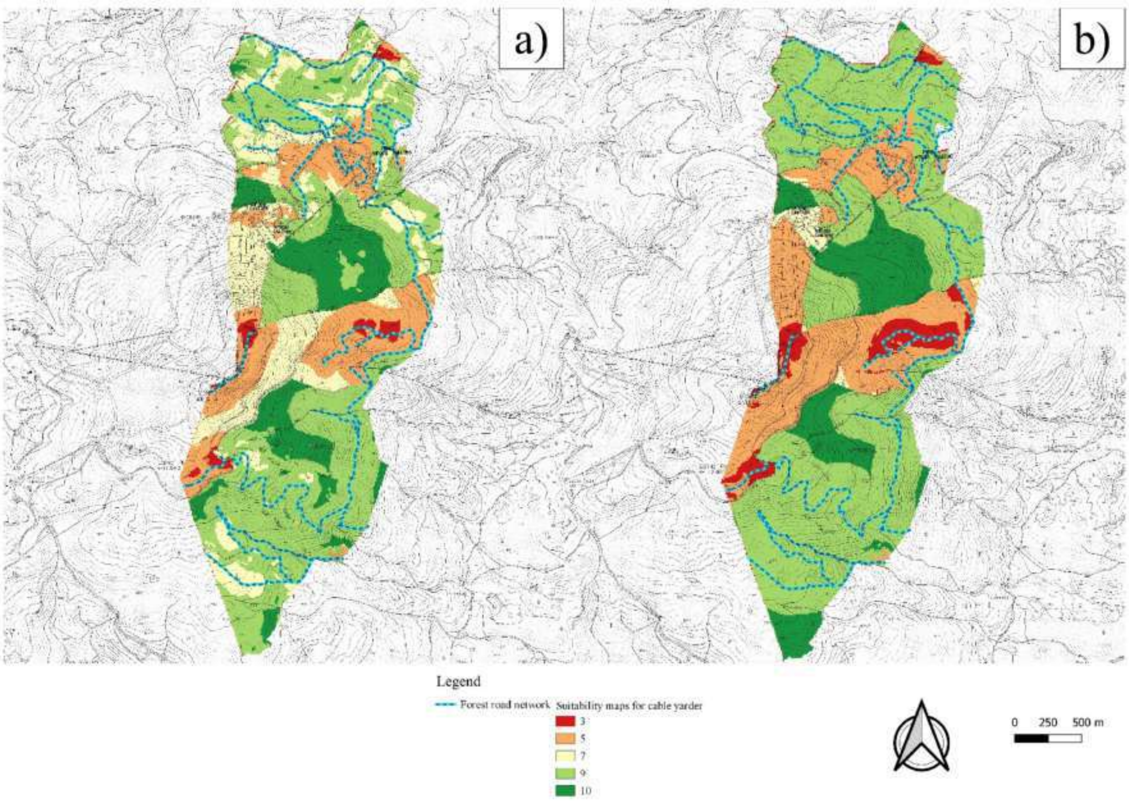

Figure 4. (**a**) Suitability map for forwarder, derived from the analysis with RTS input data. (**b**) Suitability map for forwarder, derived from the analysis with OS input data.

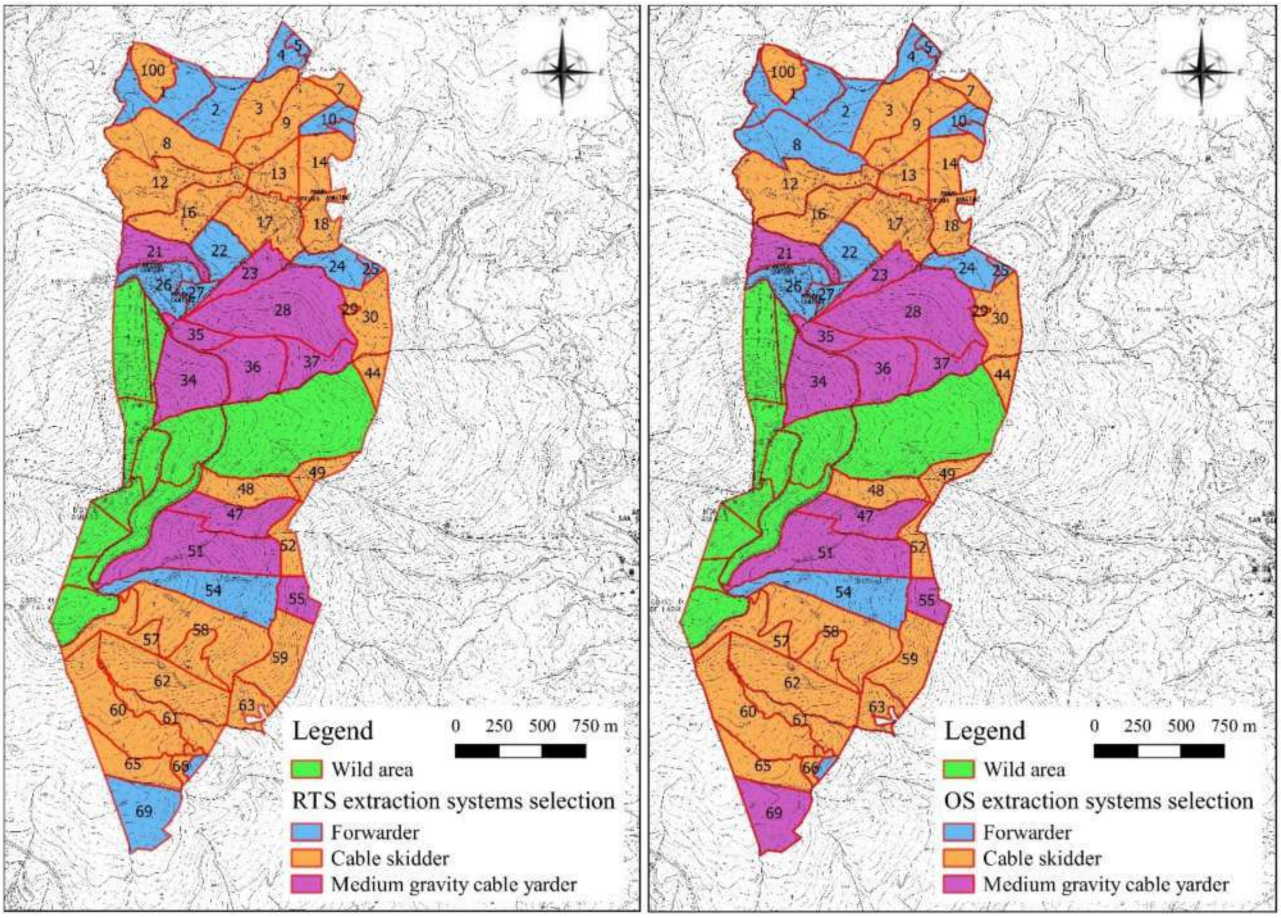

Figure 5. RTS extraction method selection (on the **left**) and OTS (on the **right**). As shown, the two predictions differ only for two sub-compartments (no. 8 and no. 69). In sub-compartment 8 (northwest of the study area), RTS indicated the cable skidder as an option, while OS selected the forwarder. In sub-compartment 69 (south of the study area), RTS selected the forwarder while OS the cable yarder.

It can also be seen that only two of the fifty-one investigated sub-compartments changed the selected extraction method from RTS to OS. In particular, in sub-compartment 8 (northwest on the study area), RTS indicated the cable skidder as an option, while OS selected the forwarder. In sub-compartment 69 (south of the study area), instead RTS selected the forwarder while OS the cable yarder.

Such differences can be attributed to the different weights that RTS and OS gave to the different criteria for the various extraction methods. In sub-compartment 8, the selection of the cable skidder by RTS can be related to the higher weight that the researcher and technicians assigned to the criterion road density for this extraction method (RD, 0.259 in RTS and 0.155 in OS, Table 3). The RD value in sub-compartment 8 is not particularly high, i.e., 153 m ha^{-1}, corresponding to a score of 5 for the cable skidder while only 4 for the forwarder (Table 2). The fact that this criterion had a relatively high weight, as in RTS, led to the selection of the cable skidder as the best alternative, while the lower weight in OS probably allowed for the assignment of the forwarder as the best option.

The change in sub-compartment 69 (from the forwarder in RTS to the medium-gravity cable yarder in OS) could instead be related to the higher weight that forest operators assigned to the criterion ED (extraction distance). Table 4 shows that ED weight in RTS was 0.161 and 0.228 in OS. As reported in Table 2, the average score for this criterion in sub-compartment 69 was 4 for the forwarder and 5 for the cable yarder. Therefore, such differences could be at the base of the shift from the forwarder to the cable yarder in this sub-compartment.

Thus, considering what is reported above, it can be stated that the applied GIS-AHP methodology showed good performance and high consistency in the selection of the best alternative among different extraction methods.

This statement was further confirmed by the results of the paired samples *t* test, carried out comparing the values of the overall suitability of the different extraction methods in the various sub-compartments according to both RTS and OS input data.

No statistically significant differences ($p < 0.05$) were found for both the forwarder suitability values and the cable skidder ones. Only the medium-gravity cable yarder showed statistically significant differences. However, as previously stated, the low level of difference did not lead to many variations in the definition of the best option for timber extraction between RTS and OS. The results of the paired samples *t* test are given in Table 5.

Table 5. Paired samples *t* test results. * indicates statistically significant differences ($p < 0.05$).

Paired Samples *t* Test, Significance Level $p < 0.05$				
	Average	**Standard Deviation**	***t***	***p***
Forwarder RTS	8	1.1		
Forwarder OS	8	1.2	−1.0000	0.322126
Cable skidder RTS	9	1.6		
Cable skidder OS	9	1.6	1.0000	0.322126
Medium gravity cable yarder RTS	8	1.5		
Medium gravity cable yarder OS	9	1.5	−2.36247	0.022086 *

Spearman correlation analysis was performed to evaluate the various parameters, and which ones had the highest influence in the selection of a given extraction method with the applied methodology. The results of this elaboration are given in Table 6.

There was a significant positive correlation among the selection of the extraction method with the forwarder and the parameters of the extracted timber amount (ETA) and soil bearing capacity (SBC). While a significant negative correlation was observed for slope (S) and extraction distance (S), for these last parameters, the correlation is not as strong as the other ones. Focusing on the cable skidder, there is a presence of a strong positive correlation with road density (RD) as well as a negative correlation with the extraction distance (ED). For the selection of the cable yarder, the most important parameters were slope (S) and extraction distance (ED).

The obtained results confirmed that the forwarder is considered suitable in the condition of high soil bearing capacity, considering the large amount of forest area that this machinery has to travel as a consequence of the low working distance. No systems showed significant correlation for roughness, which would be expected to be an important parameter when dealing with ground-based extraction.

A possible further development of this study, under the point of view of a practical implementation at the management level, could be the introduction of economic parameters and analysis, which could be integrated into the GIS environment [55]. Starting from the selection of the most suitable harvesting system, and considering the costs of the harvesting machineries and the ones related to the maintenance of the forest road network, it will be possible to evaluate the cost effectiveness of the various logging interventions and estimating in advance the stumpage value of the various interventions [69–71].

Table 6. Results of Spearman correlation analysis. In bold, statistically significant results ($p < 0.05$).

	Spearman R	*p* Level
Forwarder and RD	0.244	0.084
Forwarder and ETA	**0.570**	**0.001**
Forwarder and RG	−0.045	0.751
Forwarder and SBC	**0.534**	**0.001**
Forwarder and S	**−0.485**	**0.001**
Forwarder and ED	**−0.300**	**0.033**
Cable Skidder and RD	**0.832**	**0.001**
Cable Skidder and ETA	**0.311**	**0.026**
Cable Skidder and RG	−0.011	0.938
Cable Skidder and SBC	0.160	0.262
Cable Skidder and S	−0.240	0.090
Cable Skidder and ED	**−0.856**	**0.001**
Cable Yarder and RD	−0.220	0.121
Cable Yarder and ETA	0.169	0.236
Cable Yarder and RG	−0.261	0.064
Cable Yarder and SBC	−0.078	0.589
Cable Yarder and S	**0.432**	**0.002**
Cable Yarder and ED	**0.370**	**0.008**

4. Conclusions

The application of precision forestry and GIS has been identified as a powerful tool for the implementation of Sustainable Forest Management. The outcome of this work confirms the importance of statistical–mathematical approaches in order to support the decision-making process in applied management.

At the planning level, there are some problems with these approaches which place more emphasis on the practical implementation in real forest yards. Adequate operators, engineers, and manager training could help to improve the sustainability of forest management.

All in all, the authors applied a GIS-AHP approach to select the best alternative from among three different methods for timber extraction in a Mediterranean mountainous context. The analysis was carried out with an open-source GIS software and relying on input data for the AHP from a pool of experts from different parts of the world, which was substantially higher than the one presented in previous similar studies. This substantial amount of input data, and the fact that such data came from all over the world, overcame the rather local approach which is generally intrinsic in this kind of study. The results obtained consisted mostly of the AHP weights for the various criteria to select the extraction method, which can be taken and applied worldwide in every FMP where there is a need to choose the best alternative for timber extraction. Most rely on machinery specifically developed for harvesting purposes, which have shown the highest level of comprehensive sustainability. Moreover, considering the AHP results from the present study, each forest manager who has to draft an FMP can apply such procedures with a simple map algebra procedure, performable with open-source software and medium-sized hardware. In contexts which are different from the one reported in this case study and in the case that the managers want to evaluate the suitability of different extraction systems, such as for instance, animals or a chute system, the procedure has to be repeated while applying different weights and criteria classes.

Furthermore, an important aspect of this study consists of trying to carry out a consistency check for the obtained results. This is a difficult issue when dealing with harvesting methods selection, because it is rather complicated to assert that the selected option is actually the best one. The idea of comparing the results obtained from a survey based on a pool of researchers and forest engineers (RTS) is to be taken as a target simulation to be evaluated. The target simulation based on data derived from a pool of expert forest operators (OS) is then used to check the results of the other type of simulation. This tool for comparison and evaluation is an innovative aspect in this field of study.

The results obtained from the consistency check were encouraging, considering that, for 51 sub-compartments, only two changed the selected extraction system from between RTS to OS. We suggest that future research is performed to gain more knowledge in the evaluation of cable yarder extraction. It is worth noting that the cable yarder extraction showed statistically significant differences in the suitability values between RTS and OS. Therefore, the development of a software or web tool implementing the applied algorithms would give forest managers from all the world the opportunity to create their own simulation, helping to gain significant advantages in the process of FMP. A further step could be the implementation of algorithms to evaluate the different extraction systems under the economic point of view considering the features of the various sub-compartments, providing the managers with a tool able to predict the stumpage value of the various stands.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13030484/s1, Figure S1: Map for the criterion extraction distance, measure unit is m; Figure S2: Map for the criterion slope, measure unit is %; Figure S3: Map for the criterion extracted timber amount, measure unit is m3 ha-1; Figure S4: Map for the criterion road density, measure unit is m ha-1; Figure S5: Map for the criterion roughness, measure unit is %; Figure S6: Map for the criterion soil bearing capacity, measure unit is kPa.

Author Contributions: F.L.: Conceptualisation, Methodology, Formal Analysis, Investigation, Writing—Original Draft, Writing—Review and Editing. W.S.: Methodology, Investigation, Writing—Original Draft, Writing—Review and Editing. R.V.: Methodology, Investigation, Writing—Original Draft, Writing—Review and Editing. D.T.: Conceptualisation, Methodology, Investigation, Writing—Original Draft, Writing—Review and Editing. R.P.: Conceptualisation, Methodology, Writing—Review and Editing, Supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors gratefully acknowledge Macchia Faggeta Company, Abbadia San Salvatore—Italy. This research was carried out in part within the framework of the MIUR (Italian Ministry for Education, University and Research) initiative "Departments of Excellence" (Law 232/2016), WP3, which financed the Department of Agriculture and Forest Science at the University of Tuscia. This research was carried out in part within the project PLANNING CHANGE (CAMBIO PIANO), PSR 2014-2020 Tuscany Region, met. Leader. Meas. 16.2—Gal F.A.R. Maremma.

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

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8.2 A Preliminary Validation and Assessment of a GIS Approach Related to Precision Forest Harvesting in Central Italy. Stefanoni, W., Tocci, D., Latterini, F., Venanzi, R., Gaglioppa, P., Pari, L., Picchio, R. - (2023) FORESTS

Abstract

There has been a growing awareness of the need for sustainable forest management among forest engineers during the last decades. The selection of the best harvesting system for logging operations plays a fundamental role in this effort. Nowadays, in the decision-making process, forest engineers rely on their own experience, and it is to be expected that their evaluation of the level of appropriateness may be biased. There may be a potential solution to this problem in the implementation of AHP (Analytic Hierarchy Process) in the GIS (Geographic Information System) environment. The application of AHP gives objective information and thus reduces the level of bias in deciding which logging harvest system is best to use. The aim of this study was to evaluate the reliability of a GIS-AHP approach applied to the development of the harvesting plan of a public forest estate in Central Italy. Three extraction methods were considered: forwarder, cable skidder, and all-terrain cable yarder. Thus, the GIS-AHP model was run by relying on the basic data attainable from the local forest management plan and then on detailed information provided by field data collected from 10 harvested blocks. Among these, in three blocks, the logging harvest method was changed from forwarder to cable skidder. Statistically significant differences were found between the suitability values obtained from the forest management plan and those retrieved from the field surveys for the forwarder and cable skidders but not for all-terrain cable yarders.

Keywords: Territorial Information System; precision forest harvesting; forwarder; cable skidder; cable yarder; timber extraction; forest operations.

forests

Article

A Preliminary Validation and Assessment of a GIS Approach Related to Precision Forest Harvesting in Central Italy

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Abstract: There has been a growing awareness of the need for sustainable forest management among forest engineers during the last decades. The selection of the best harvesting system for logging operations plays a fundamental role in this effort. Nowadays, in the decision-making process, forest engineers rely on their own experience, and it is to be expected that their evaluation of the level of appropriateness may be biased. There may be a potential solution to this problem in the implementation of AHP (Analytic Hierarchy Process) in the GIS (Geographic Information System) environment. The application of AHP gives objective information and thus reduces the level of bias in deciding which logging harvest system is best to use. The aim of this study was to evaluate the reliability of a GIS-AHP approach applied to the development of the harvesting plan of a public forest estate in Central Italy. Three extraction methods were considered: forwarder, cable skidder, and all-terrain cable yarder. Thus, the GIS-AHP model was run by relying on the basic data attainable from the local forest management plan and then on detailed information provided by field data collected from 10 harvested blocks. Among these, in three blocks, the logging harvest method was changed from forwarder to cable skidder. Statistically significant differences were found between the suitability values obtained from the forest management plan and those retrieved from the field surveys for the forwarder and cable skidders but not for all-terrain cable yarders.

Keywords: Territorial Information System; precision forest harvesting; forwarder; cable skidder; cable yarder; timber extraction; forest operations

Citation: Stefanoni, W.; Tocci, D.; Latterini, F.; Venanzi, R.; Gaglioppa, P.; Pari, L.; Picchio, R. A Preliminary Validation and Assessment of a GIS Approach Related to Precision Forest Harvesting in Central Italy. *Forests* **2023**, *14*, 127. https://doi.org/10.3390/f14010127

Academic Editor: Raffaele Cavalli

Received: 24 November 2022
Revised: 5 January 2023
Accepted: 7 January 2023
Published: 10 January 2023

1. Introduction

The European Green Deal approved in 2020 envisions the EU leading the transition towards green energy during the next decades [1]. In fact, the EU is expected to reach 32% of domestic energy production made from renewable resources [2–4]. Hence, conscientious use and management of available lands are mandatory to avoid overexploitation. In the forestry sector, the growing public awareness regarding the sustainable exploitation of natural resources is also increasing the expectations of both scholars and forest engineers to apply methods that provide better sustainability in activities for wood production [5,6]. Sustainable exploitation of medium-large forests can be guaranteed by drawing a proper Forest Management Plan (FMP) that includes recommendations for on-site activities, such as forest logging, silviculture, and road construction, which are planned for the following 5–20 years [7,8].

During the last decades, the use of Geographic Information Systems (GIS) for agriculture and forestry planning has gained interest for the vast panorama of possible applications [9–11]. The most interesting feature is combining spatial and non-spatial information to facilitate decision-making, for instance, in feedstock supply chains or FMP [12].

Dealing with all those critical aspects involved in forest management is definitely not a simple task to accomplish, but it is crucial in Sustainable Forest Management (SFM) [13,14]. A tangible contribution can be given by setting proper harvesting operations [15–17]. In fact, with improvements in this phase of the supply chain, the environmental impact of wood products can be significantly reduced while creating better working conditions for employees [18]. Physical characteristics of the soil, accessibility, infrastructures, and purpose of the forestry interventions are the main driving factors to consider in this kind of Multi-Criteria Decision Analysis (MCDA) [19]. In fact, this tool holistically evaluates different alternatives that may result from the combinations of these factors [8,20,21]. Among the several MCDA methods known, the Analytic Hierarchy Process (AHP) [22] is the most commonly applied to this sector. A pairwise comparison is applied to elements having the goal set at the higher level, while criteria and alternatives are set at the lower levels [16].

In the context of Italian forestry, the duration of an FMP is generally 10 years. According to the various Italian forestry regulations, which are slightly different among the various regions, FMP is mandatory for public forest estates and also strongly recommended for private ones, with some exceptions. An example is the Tuscany region, in which FMP is also mandatory for private forest estates with more than 100 ha of forest surface. Within that period, the Executive Harvesting Plan (EHP) for every cutting block that is greater than a given surface and will undergo harvesting operations must be reported prior to the beginning of harvesting. There is a different limit for each region. The EHP made according to the general recommendations provided in the FMP must include the details of the amount of retrieved biomass and the description of the harvesting operations to be performed, including felling, processing, and extraction techniques that are to be implemented in that given cutting block. This type of two-step procedure makes it difficult to predict what could impact forest operations on the local environment, economy, and social aspects in the long term since only the EHP will contain specific procedures that are applied in the field. Although the procedures, approaches, and application of the best practices will be in compliance with the criteria of Sustainable Forest Management (SFM) [23–25] and Sustainable Forest Operations (SFOs), such as the Reduced Impact Logging (RIL) [26,27], it is still unknown what the applied harvesting system is until the executive project is delivered. Furthermore, this kind of decision derives from an in situ analysis carried out by the local forest engineer, who is the developer of the EHP. On the other hand, it is strongly suggested to include forest harvesting planning in FMP development, as recommended by scholars in the forestry sector [13]. Objectivity in the selection of a given harvesting system is necessary for the context of forest operations planning, currently considering that this selection is often based on the experience of the forest engineer working in the field rather than on an objective evaluation. The application of GIS-AHP for the selection of the harvesting system at the cutting block level has been proven to be an effective tool to increase objectivity in the choice [19]. However, it is important to highlight that the efficacy of the GIS-AHP method is strictly related to the resolution of entry data; that is, the higher the resolution, the more trustable the output is [28]. Currently, such a limit is still not defined in the forestry sector via a direct comparison between operations suggested within the FMP or the actual operations conducted on the field after the application of EHP.

Therefore, the aim of this study was to probe the reliability of applying the GIS-AHP method in predicting the actual field operations to conduct in the forestry sector by direct comparison of GIS-AHP outputs produced relying on FMP data, with field data collected after the harvesting in a real case study of a forest in Central Italy. The possibility of extensively applying such methods will improve the decision-making process of selecting the most suitable extraction method for a given area. Moreover, it will be less time-consuming and provide non-biased decisions.

2. Materials and Methods

2.1. Study Area

The study focuses on the Natural Reserve Selva del Lamone, which is located in Central Italy, Latium Region, Farnese Municipality. The reserve covers an area of approximately 2000 ha. The average annual precipitation in the area is 1000 mm, with the highest precipitation in November and the lowest in July. Terrain morphology consists of a volcanic plateau with an alternation of fresh and fertile soils and zones with a high accumulation of rocks with lesser fertile soils. The main species of the area is turkey oak (*Quercus cerris* L.), but there are also several different tree species mixed with turkey oak, such as *Acer campestre* L., *Quercus pubescens* Willd., *Acer monspessulanum* L., *Fraxinus ornus* L., *Quercus* × *crenata* Lam., and *Ulmus minor* Mill.

Forest management is based on the coppice system; however, the abandonment of rural zones, which has occurred in the last decades, has led to the partial abandonment of forestry in several zones of the reserve. Therefore, a major part of the coppice cutting blocks is currently much beyond the conventional rotation age, which is about 20 years, with various degrees of transition to the high forest in the high fertility zones. Forest stands now have a structure that is very similar to those of even-aged high forests, while in the less fertile area, the polycormic structure of coppice is still evident, notwithstanding that the age is twice the conventional rotation age. The current forest management plan is valid for the 2016–2025 period and provides the maintenance of the coppice system in the cutting blocks with a lower age (<30 years), while in the other cutting blocks of higher age, thinning interventions that favor and accelerate the transition to the high forest is provided. In the zones with lower accessibility, the FMP provides no intervention at all, leaving such stands to the natural evolution. An aerial image of the study area is reported in Figure 1.

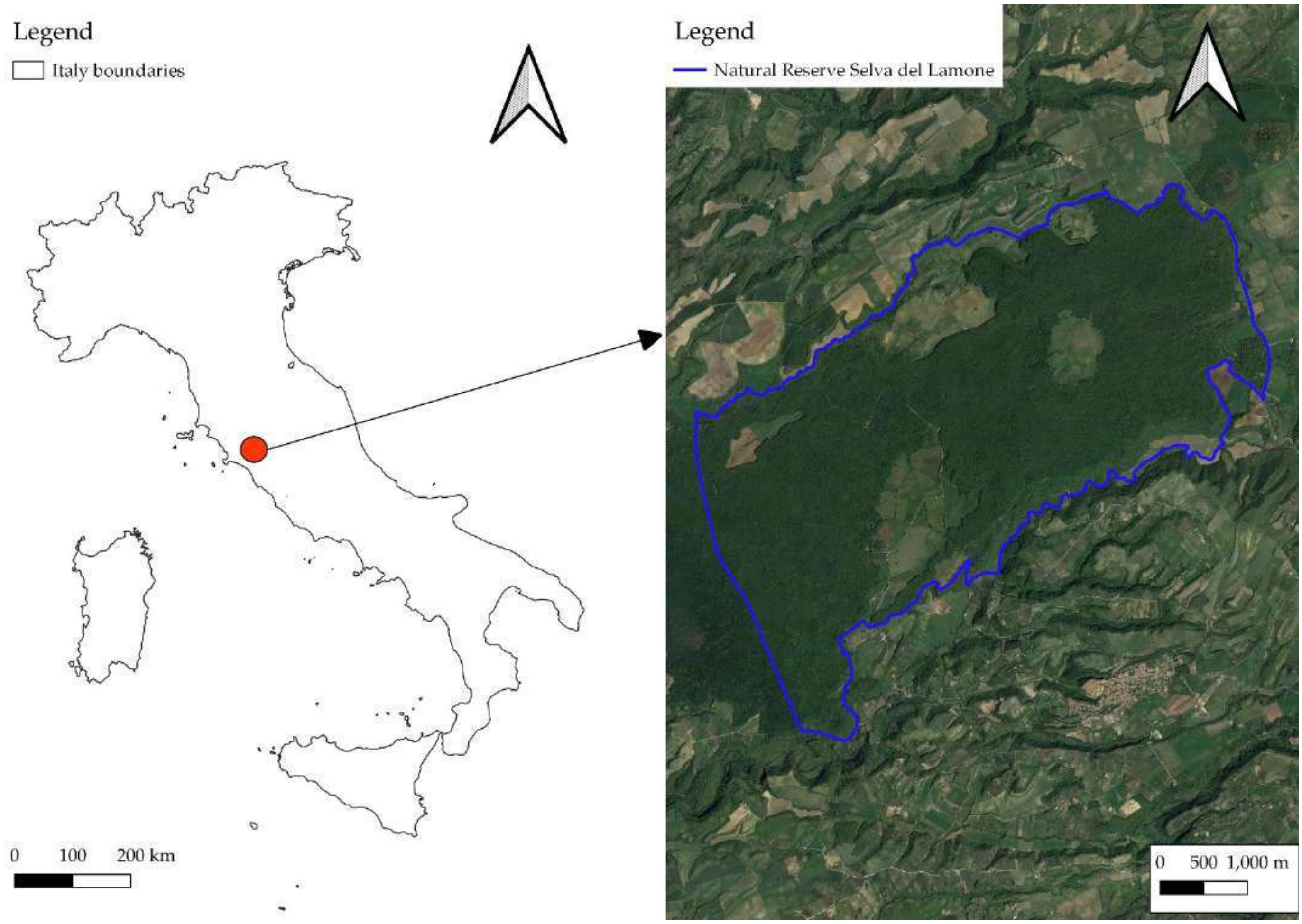

Figure 1. Aerial image of the study area and location within Italy.

2.2. Methodological Framework

In the context of Italian forestry, with particular reference to Central and Southern Italy, forest engineers develop the FMP based on their own field surveys. Then, along the 10-year duration of the FMP, the forest engineer also carries out other field surveys for each cutting block to develop the EHP. In other words, FMP offers general guidelines for large surfaces of hundreds or thousands of hectares. It is required that an EHP is written for an area of 5–20 hectares shortly before harvesting. This provides more accurate information since forest engineering is required to perform local surveys.

A three-step procedure was implemented with the GIS software, Quantum GIS 3.16, to answer the question behind the experimental design. Firstly, the selection of the most suitable extraction system for each cutting block of the FMP was implemented with a GIS-AHP procedure, as described by Latterini et al. [29], by relying on a 10 m resolution Digital Elevation Model (available for free download for all national territory [30]) and the data retrieved from the FMP. The applied GIS-AHP procedure takes into consideration six variables that can influence the forest engineer in the selection of the extraction system. The only focus is on extraction operations exclusively carried out by chainsaw in the study area by forwarder, cable skidder, and all-terrain cable yarder. These variables are slopes of the area (%), road density (m ha^{-1}), extraction distance (m), terrain roughness (%), soil-bearing capacity (kPa), and extracted timber amount (m^3 ha^{-1}). Maps related to the six variables for the study area are reported in the Supplementary Materials (Figures S1–S6). The values of each variable for the study area are retrieved and implemented into the GIS environment. At the same time, the AHP procedure is carried out to define the relative weights of each variable in the selection of each one of the considered tree extraction systems.

The procedure for implementing the GIS-AHP procedure to identify the most suitable extraction system can be summarized in the following steps: We obtain the data from six variables of interest for the study areas in raster format; We define the hierarchy of importance of the variables; We retrieve the relative weights for the variables by the AHP by interviewing experts on the topic through the development of pairwise comparison matrices; We apply a map algebra procedure consisting of a weighted average between the values of the six variables and their relative weights. This allows us to obtain a raster map that reports the suitability value for a given extraction system in each pixel. Therefore, in the present case, three suitability maps are obtained: one for the forwarder, one for the cable skidder, and one for the all-terrain cable yarder. Finally, the median value of suitability for each cutting block is extracted through a resampling procedure, and the extraction system with the highest median value of suitability in a given cutting block is considered the most suitable.

A detailed description of the methodology for the GIS-AHP procedure can be found in Latterini et al. [29]. The applied AHP weights are the ones obtained by Latterini et al. [29] after interviewing a wide pool of forest harvesting experts from all around the world (Table 1).

Table 1. AHP pairwise comparison matrix and weights [29]. S: slope; ED: extraction distance; SBC: soil-bearing capacity; ETA: extracted timber amount; RD: road density; RG: terrain roughness; CR: consistency ratio (must be < 0.1 for the AHP weights to be considered reliable).

Forwarder								
Criteria	**S**	**ED**	**SBC**	**ETA**	**RD**	**RG**	**Weights**	**CR**
S	1	1	0.5	1	1	1	0.143	0.0001
ED	-	1	0.5	1	1	1	0.143	
SBC	-	-	1	2	2	2	0.286	
ETA	-	-	-	1	1	1	0.143	
RD	-	-	-	-	1	1	0.143	
RG	-	-	-	-	-	1	0.143	
Cable Skidder								
Criteria	S	ED	SBC	ETA	RD	RG	Weights	CR
S	1	0.5	1	2	0.5	1	0.136	0.002
ED	-	1	2	3	1	2	0.259	
SBC	-	-	1	2	0.5	1	0.136	
ETA	-	-	-	1	0.3333	0.5	0.075	
RD	-	-	-	-	1	2	0.259	
RG	-	-	-	-	-	1	0.136	
All-terrain Cable Yarder								
Criteria	S	ED	SBC	ETA	RD	RG	Weights	CR
S	1	1	3	0.3333	1	3	0.161	0.01
ED	-	1	3	0.3333	1	3	0.161	
SBC	-	-	1	0.2	0.3333	1	0.06	
ETA	-	-	-	1	3	5	0.399	
RD	-	-	-	-	1	3	0.161	
RG	-	-	-	-	-	1	0.06	

Secondly, ten cutting blocks were randomly selected (Figure 2), and in these cutting blocks, detailed surveys to retrieve data on the six above-mentioned variables were carried out.

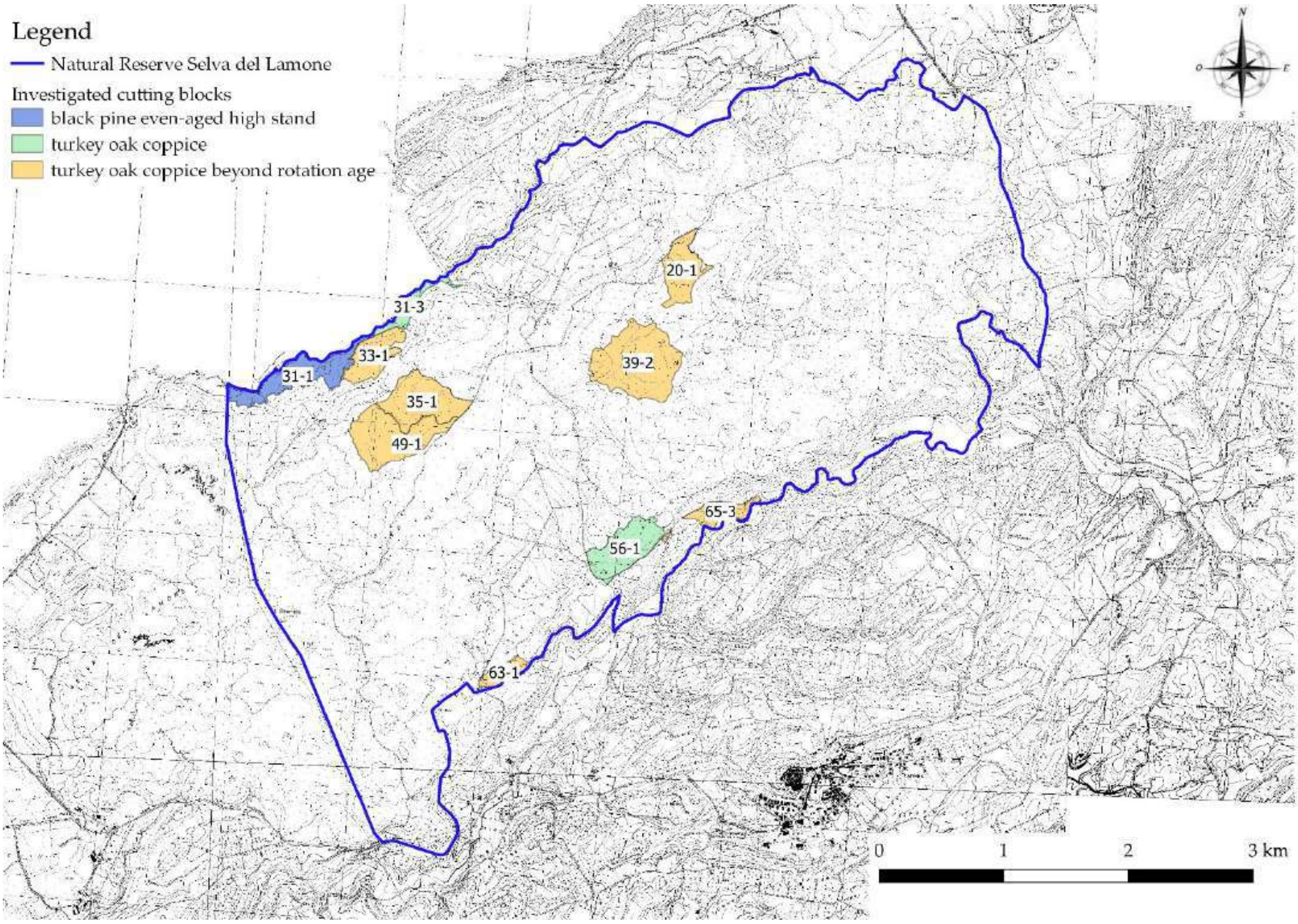

Figure 2. Details of the investigated cutting blocks.

The slope was measured by a clinometer (Haglöf, Långsele, Sweden) in a number of sample points ranging from 100 to 200 per cutting block, depending on the surface of the cutting block. Then, a Delaunay triangulation (TIN) algorithm was used to develop a 2 m resolution Digital Terrain Model (DTM). A detailed survey of the viability present in each cutting block was performed to evaluate road density by recording the track of each road with a handheld GNSS receiver, uploading the data into the GIS software, and converting them into a line shapefile. The methodology proposed by Picchio et al. to calculate topographic extraction distance, accounting for terrain slope [31], was implemented relying on the TIN DTM and the above-mentioned shapefile of road density. Soil-bearing capacity was measured in 20–30 sample points in each cutting block, depending on the dimension of the cutting block, with a light falling weight deflectometer TERRATEST® 4000 (Lehnitz/Berlin, Germany). Then, a TIN interpolation was carried out as well to obtain raster maps of soil-bearing capacity for each cutting block. Terrain roughness was assessed according to the methodology proposed in the Italian National Forest Inventory [32]. Ten transects measuring 2 m in width and 50 m in length, corresponding to 100 m^2, were randomly selected within the surveyed cutting blocks. For each transect, obstacles (i.e., rocks, ditches, and fences) measuring more than 50 cm in absolute height were counted and measured for area assessment. Thus, terrain roughness in terms of percentage was calculated as the ratio between the total area of obstacles and the area of the transect. The threshold of 50 cm was selected because, considering alternatives for ground-based extraction machinery specifically developed for forestry (such as skidders and forwarders), rocks of lower height are not considered an obstacle for such machines. Finally, sample plots were established in each of the investigated cutting blocks to assess the standing volume and extracted timber amount. The sample plot surface was established to cover at least 10% of the overall cutting block surface. In each sample plot, the diameter at breast height (dbh–cm) was measured for all trees with a caliper, and the height of 50 trees belonging to different dbh classes was measured as well with a Vertex 5 hypsometer (Haglöf, Långsele, Sweden). Local allometric equations were used to estimate standing volume. For the estimation of the extracted timber amount, a simulation of the felling choice was carried out, annotating the diameter of the trees to be theoretically felled depending on the kind of treatment (coppicing or thinning) and estimating their volumes with the local allometric equations. An overall description of the different surveys carried out for the development of FMP and the second step of the present work are reported in Table 2.

Table 2. Description of the surveys carried out by the local forest engineer for the development of the FMP and by the authors of the present work.

Variable	FMP	This work
Slope (%)	A 10 m DEM available for free download	Sampling points in the cutting blocks and TIN interpolation to develop a 2 m DTM
Road density (m ha^{-1})	Shapefile was developed by relying on available topographic maps and on the basis of the previous EHPs	Field surveys and recording of the tracks by GNSS receiver
Extraction distance (m)	Calculation accounting on the shapefile of roads	Calculation of topographic distance relying on the shapefile of roads and the 2 m DTM
Terrain roughness (%)	Visual assessment	Direct measurement by transects
Soil-bearing capacity (kPa)	Visual assessment	Assessment by deflectometer and TIN interpolation
Extracted timber amount (m^3 ha^{-1})	Sample plots (generally 800–1000 m^2 per cutting block) for estimating standing volume and fixed percentage of removal to estimate extracted timber amount (85% for coppicing and 30–40% for thinning)	Sample plots (covering at least 10% of the cutting block surface) and detailed assessment of the trees to be removed, estimating their volumes separately

Finally, the GIS-AHP procedure was repeated for the ten selected cutting blocks relying on the data collected during the field surveys to assess if, in these cutting blocks, the suggested extraction system was the same as the one suggested by the GIS-AHP procedure based on the retrieved data from the FMP.

2.3. Statistical Analyses

The statistical analysis concerned the evaluation of the differences between the suitability values for each extraction system in the investigated cutting blocks for the calculation starting from FMP data and from the detailed field surveys. The aim of the statistical analysis was to identify the variables where changing values were responsible for a variation in the suitability values.

The paired-sample Wilcoxon test was applied to investigate the differences between the suitability values calculated starting from the different input data, considering that the data did not meet the requirement of normality, making it impossible to apply a paired-sample t-test. Spearman's rank correlation coefficient was calculated to investigate the correlation between a change in the suitability values for a given harvesting system and a change in the values of the variables moving from FMP data to data collected in the field.

All the statistical analyses were carried out using Statsoft Statistica software version 7.0 (Tulsa, OK, USA), considering a significance threshold of $p < 0.05$.

3. Results

3.1. Identification of the Most Suitable Extraction System

The identification of the most suitable extraction system for all the cutting blocks of the study area is reported in Figure 3. Forwarders were the prevalent type of machine identified as the most suitable in a major part of the study area, that is to say, about 64% of the cutting blocks corresponding to 77% of the overall surface. Cable skidders were considered the most suitable alternative in about 24% of the cutting blocks, corresponding to 14.52% of the study area, particularly in those cutting blocks characterized by a low amount of extracted timber and located close to the existing road network. It is possible to notice that such cutting blocks are mostly located in the northern part of the study area. Finally, all-terrain cable yarders were suggested in only 12% of the cutting blocks, which is 8.75% of the study area surface, particularly in the cutting blocks with low soil-bearing capacity, a higher amount of extracted timber, and those in which the forest management plan provides intervention of coppicing with 80–90 standards per hectare.

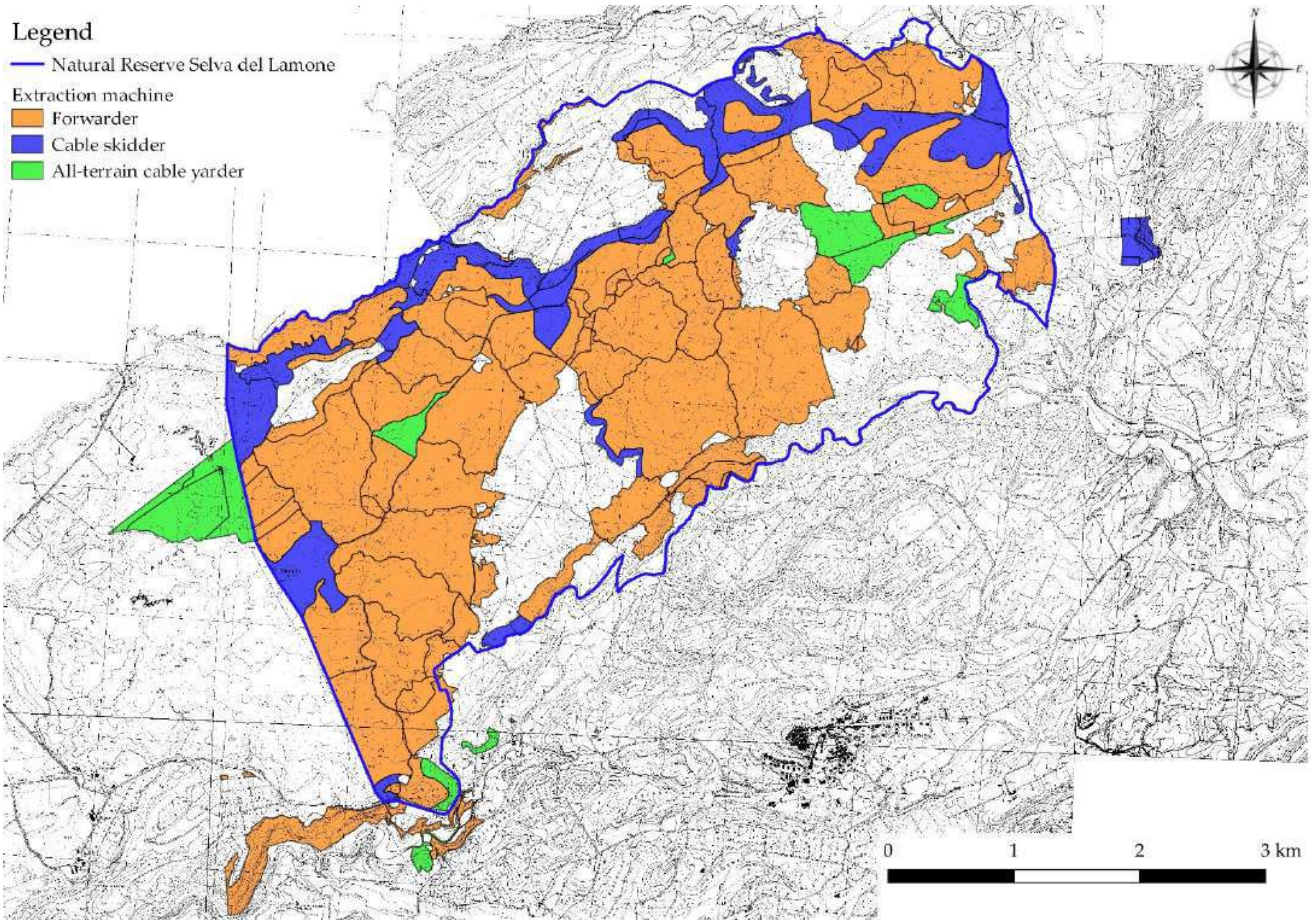

Figure 3. Extraction system suggested by the GIS-AHP procedure in all the cutting blocks of the study area. It is important to notice that there are some cutting blocks outside the boundaries of the

Natural Reserve Selva del Lamone. However, these cutting blocks, even if outside the reserve's territory, are managed by the Natural Reserve concerning forest management issues.

3.2. Evaluation of the Results of the GIS-AHP Procedure

The values of the investigated variables calculated from the FMP surveys and from the field surveys carried out in the framework of the present study are given in Table 3. Values of the slope, extracted timber amount, roughness, and soil-bearing capacity changed when moving from FMP data to field surveys. Interestingly, data related to the road network density did not change. This is because the detailed field survey related to tracking road density did not report any other road than the ones already reported in the FMP forest road map. However, as a consequence of the calculation carried out with two different terrain models, the values of extraction distance also changed between FMP and field surveys. Indeed, the applied methodology for the calculation of extraction distance provides an orographic distance, which takes into account the slopes.

Table 3. Values of the six variables used for the GIS-AHP procedures were calculated from FMP data and from the field surveys carried out in the present study.

			FMP				
Cutting block	Intervention	Slope (%)	Extracted timber amount (m^3 ha^{-1})	Road density (m ha^{-1})	Extraction distance (m)	Roughness (%)	Soil-bearing capacity (kPa)
20-1	Thinning	6.71	60	82.38	121.92	20	60
31-1	Thinning	11.51	50	75.49	48.63	20	60
31-3	Coppicing	13.26	150	156.68	41.57	20	60
33-1	Thinning	13.21	58	75.38	90.89	35	80
35-1	Thinning	6.14	50	54.19	122.33	45	80
39-2	Thinning	6.44	55	0.00	544.31	35	70
49-1	Thinning	5.38	50	7.63	274.20	45	80
56-1	Coppicing	8.81	125	63.38	108.68	20	60
63-1	Thinning	6.04	35	158.50	37.03	20	60
65-3	Thinning	23.85	35	131.54	56.09	35	80
				Field surveys			
Cutting block	Intervention	Slope (%)	Extracted timber amount (m^3 ha^{-1})	Road density (m ha^{-1})	Extraction distance (m)	Roughness (%)	Soil-bearing capacity (kPa)
20-1	Thinning	10.91	50.34	82.38	118.23	29	69
31-1	Thinning	5.11	77.00	75.49	46.87	1	70
31-3	Coppicing	6.99	100.30	156.68	39.54	1	70
33-1	Thinning	15.48	90.90	75.38	88.21	1	89
35-1	Thinning	3.31	27.99	54.19	109.36	18	90
39-2	Thinning	5.31	60.76	0.00	487.25	23	79.5
49-1	Thinning	9.81	41.40	7.63	256.21	18	90.5
56-1	Coppicing	5.81	101.35	63.38	104.29	27	70
63-1	Thinning	11.12	42.60	158.50	36.01	21	70
65-3	Thinning	12.14	38.40	131.54	51.26	12	90

As a result of these changes in the variable values, three of the ten tested cutting blocks (31-1, 33-1, and 65-3) changed the suggested extraction system, in particular, shifting from forwarder to cable skidder (Table 4). In all of the three cutting blocks that changed, the suggested extraction system and scheduled intervention according to the forest management plan were thinning.

Table 4. Suggested extraction system for the investigated parcels with the output of the GIS-AHP procedure developed by the FMP data and field surveys carried out in the framework of this study. The ***italic bold*** indicates the cutting blocks with a different suggested extraction system between the two simulations.

Cutting block	Field surveys	FMP
20-1	Forwarder	Forwarder
31-1	***Cable skidder***	***Forwarder***
31-3	Cable skidder	Cable skidder
33-1	***Cable skidder***	***Forwarder***
35-1	Forwarder	Forwarder
39-2	Forwarder	Forwarder
49-1	Forwarder	Forwarder
56-1	Forwarder	Forwarder
63-1	Cable skidder	Cable skidder
65-3	***Cable skidder***	***Forwarder***

Statistical analyses were carried out to check the difference between the suitability values of the three extraction systems, while the data calculated from FMP and field surveys highlighted significant differences in the suitability values of forwarders (Wilcoxon test $z = 2.0226$ and $p = 0.0431$) and cable skidders (Wilcoxon test $z = 2.3664$ and $p = 0.0179$) but not for all-terrain cable yarders.

Spearman's rank correlation analysis results are reported in Table 5. Considering that only forwarders and cable skidders showed statistically significant differences in suitability values calculated with FMP and field survey data, Spearman's rank correlation analysis was only performed for these two extraction systems and not all-terrain cable yarders. Moreover, the variation in road density was null and not included in the analysis. The highest correlations were found for extracted timber amount both for forwarders (R = 0.67) and skidders (R = 0.45). For forwarders, the R-value for soil-bearing capacity (R = 0.63) is also rather high. However, no variable showed a significant correlation with the variations of suitability for both forwarders and skidders.

Table 5. Spearman's R and *p*-value for the various couple comparison between variations of suitability values for forwarder and cable skidder and variations of the six variables' values. For variation, what is meant is the difference between the values calculated from FMP data and the values retrieved after the field surveys carried out in the present study. FORW: forwarder; SKID: skidder; S: slope; ED: extraction distance; SBC: soil-bearing capacity; ETA: extracted timber amount; RG: terrain roughness.

	Spearman's R	*p*-Value
FORW and S	0.2236	>0.05
FORW and RG	−0.2294	>0.05
FORW and SBC	0.6309	>0.05
FORW and ETA	0.6708	>0.05
FORW and ED	−0.1118	>0.05
SKID and S	0.21622	>0.05
SKID and RG	−0.3028	>0.05
SKID and SBC	0.2644	>0.05
SKID and ED	−0.1261	>0.05
SKID and ETA	0.4505	>0.05

4. Discussion

4.1. Discussion of the Obtained Results

In Italy, forestry surface accounts for approximately one-third of the national territory [33]. Thus, managing such an extensive surface requires a combination of the expertise of forest engineers and the use of reliable tools. Precision forestry, with particular reference to GIS, has been proven to be an effective tool to help forest engineers in the framework of the implementation of sustainable forest operations [34]. However, without input data, which has a precision suitable for the target analysis, the precision forestry approach loses much of its effectiveness [35,36].

The aim of this study was to determine the level of accuracy of the base data that are available for Central and Southern Italy forest engineers who make the forest management plan. This study also sought to determine if the data was sufficient to develop a GIS-AHP procedure to produce a forest harvesting plan. This plan should provide information regarding the most suitable extraction system in each cutting block of the forest management plan before the actual implementation of the logging operations.

The obtained results showed that of the ten investigated cutting blocks, three changed the suggested extraction system after implementing more detailed field surveys in comparison with the ones that are typical for the development of a forest management plan. In detail, the three cutting blocks shifted the suggested extraction system from a forwarder to a cable skidder. It is evident that implementing a procedure that could potentially lead to a wrong decision 30% of the time is not suitable. However, the advantages of a preliminary harvesting plan that reduces time, labor, and management costs have been clearly highlighted by previous studies on the topic [17,37]. Therefore, the question arises of how to improve the input quality of a forest management plan's data to a suitable level to develop a proper harvesting plan.

There are several possible solutions to this question, which should be implemented altogether, considering that our results from Spearman's correlation analysis suggested that no particular variable caused a change that forced shifting in the harvesting system. Firstly, it should be worth the effort to cover all national territory with a 1 m resolution Digital Terrain Model (DTM) or at least with a Digital Elevation Model (DEM). Different European countries already have a 1 m DTM or DEM [35], while in Italy, only about 63% of the territory is covered by this kind of data [38]. This will allow an increased precision of slope maps. Although the results from Spearman's correlation analysis did not reveal any variable had a significant influence on the changing of the suitability values for the investigated extraction systems, it is, however, possible to retrieve some important information about which variables we should focus our attention on to improve the affordability of the GIS-AHP procedure. In particular, R coefficient values higher than 0.6 were achieved for the forwarder by soil-bearing capacity and extracted timber amount, and the latter was also achieved for the cable skidder with an R-value of 0.45. Therefore, it could be worth the effort to improve the precision of data regarding these two variables during the development of a forest management plan. Direct measurement of soil-bearing capacity in the field through a portable falling weight deflectometer is excessively costly and time-consuming [39,40]. However, given that soil-bearing capacity is related to other physical characteristics, such as penetration resistance [41] (which is easily measurable through handheld penetrometers [42,43]), it could be possible to include this kind of evaluation during the field surveys for the development of a forest management plan.

Regarding increasing the precision of the estimation of the amount of extracted timber prior to harvesting implementation, we understand that it is not possible to ask the forest engineer who is developing the forest management plan to increase the forest surface covered by sample plots for biomass estimation. This is indeed a time-consuming process, and to carry out a precise biomass estimation on several thousand hectares of a forest management plan is simply impossible. However, remote and proximal sensing techniques to estimate forest biomass can be very helpful in this situation [44–46]. Although these techniques are not appropriate at the level of the Executive Harvesting Plan, which requires not only the biomass estimation but also the indication of trees to be felled or released by spray, they are suitable to carry out extensive biomass estimation on large surfaces, a factor which could be very helpful for the forest engineers in the phase of forest management plan development.

4.2. Study Limitations and Future Research

Notwithstanding the interesting results obtained in the study, it is worth mentioning to the readers about our study's limitations. This study is indeed a preliminary trial performed at a case-study level. Furthermore, it only involves a single area in Central Italy. Every study dealing with the management of natural resources implies a plethora of factors, which could affect the final outcome, and therefore a single case study is not enough to shape general conclusions by itself. Future improvements should include larger areas and possible variable conditions so as to determine the limits better. It is worth mentioning, however, that the suggested approach here is fully repeatable in different study contexts, and it is able to provide answers to an important issue for forest engineers.

5. Conclusions

The implementation of AHP methods within the GIS environment has shown to be useful in selecting harvesting methods in the forestry sector, especially due to the objectiveness of the applied criteria. However, the main limiting factor is the accuracy of the input data used, such as the DTM or DEM resolution. The present case study aimed to investigate the reliability of the GIS-AHP in predicting the best harvesting method to apply to the forest in Central Italy by comparing the results with field data. The highest correlations were found between extracted timber amount and soil-bearing capacity with forwarders, while extraction distance exhibited the lowest correlation with both forwarders and skidders. Although the statistical analysis was not significant, it is noteworthy to highlight that, out of the ten cutting blocks tested, seven matched with the harvesting methods predicted by GIS-AHP. Therefore, it is reasonable to deduce that by increasing the resolution of input data, which are DTM and DEM, this tool would be made more powerful and reliable in predicting harvesting methods in the forestry sector.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14010127/s1, Figure S1: Slope map of the study area; Figure S2: Road density map; Figure S3: Extraction distance map; Figure S4: Map of extracted timber amount; Figure S5: Terrain roughness map; Figure S6: Map of soil-bearing capacity.

Author Contributions: Conceptualization, W.S., D.T., F.L. and R.P.; methodology, W.S., D.T. and F.L.; formal analysis, W.S., D.T. and F.L.; writing—original draft preparation, W.S. and D.T.; writing—review and editing, W.S., D.T., F.L., R.V., P.G., L.P. and R.P.; supervision, L.P. and R.P. All authors have read and agreed to the published version of the manuscript.

Funding: This study was carried out in cooperation with the Agritech National Research Center and received funding from the European Union's Next-Generation EU package (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)—MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4—D.D. 1032 17/06/2022, CN00000022)—beneficiary of Tuscia University—DAFNE, scientific responsible: Prof. Rodolfo Picchio. The views and opinions in this manuscript are those of the authors. They do not purport to reflect the official policies of the European Union or the European Commission.

Data Availability Statement: Data is available upon request from the corresponding author.

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

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8.3 Depth-to-Water Maps to Identify Soil Areas That Are Potentially Sensitive to Logging Disturbance: Initial Evaluations in the Mediterranean Forest Context. Latterini, F., Venanzi, R., Tocci, D., Picchio, R. – (2022) LAND

Abstract

Scientific research on reduced-impact logging has been addressed to develop effective approaches and methodologies to limit soil disturbance caused by forest operations. In recent years, the development of soil trafficability maps based on soil wetness indices is the approach that has been extensively used in the context of the Boreal forests. In particular, the depth-to-water (DTW) index has been identified as an interesting solution for the identification of areas particularly sensitive to soil disturbance. This study aimed to evaluate the cost-benefit factor of DTW maps for the identification of soil-sensitive areas in the Mediterranean context. In particular, a DTW map was developed for two oak coppice areas located in Italy and harvested over a period of 2–4 years with different mechanisation levels. Soil surveys concerning soil moisture, physico-chemical properties (bulk density, penetration resistance, shear resistance, organic matter), and biological properties (soil microarthropods community measure via soil biological quality (QBS-ar) index) were carried out in these forests, checking for significant differences between the zones at DTW index ≤1 (which should be more sensitive to soil disturbance) and the other areas of the forest soil. The results obtained revealed the efficiency of a DTW index in potential areas at a higher level of soil moisture. On the other hand, the values of soil physico-chemical properties in the areas at a DTW index ≤1 did not differ significantly from the ones in other zones. However, the values of the QBS-ar index in areas with a low DTW index were significantly lower than the ones in zones at the DTW index >1. Therefore, the obtained findings reveal that the DTW index is a reliable tool to identify and predict which areas are more prone to impact soil biological properties.

Keywords: sustainable forest operations; coppice; QBS-ar index; soil bulk density; skidding *land*

Article

Depth-to-Water Maps to Identify Soil Areas That Are Potentially Sensitive to Logging Disturbance: Initial Evaluations in the Mediterranean Forest Context

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Citation: Latterini, F.; Venanzi, R.; Tocci, D.; Picchio, R. Depth-to-Water Maps to Identify Soil Areas That Are Potentially Sensitive to Logging Disturbance: Initial Evaluations in the Mediterranean Forest Context. *Land* **2022**, *11*, 709. https://doi.org/10.3390/land11050709

Academic Editors: Lord Ameyaw and Manuel López-Vicente

Received: 30 March 2022
Accepted: 5 May 2022
Published: 9 May 2022

1. Introduction

The implementation of sustainable forest management (SFM) is one of the main goals specified in the New European Forest Strategies for 2030 [1]. One of the most important aspects to be taken into account to achieve SFM consists of implementing sustainable forest operations (SFOs). The concept of SFOs involves the development of logging activities in a way that ensures economic efficiency without compromising the health of the environment and the safety of the operators [2]. One of the main environmental targets of the SFOs is to limit disturbance to the forest soil caused by logging activities [3–5]. Soil compaction caused by machinery traffic can indeed lead to hydrological concerns such as increased runoff and erosion [6,7]. Furthermore, machinery-induced soil compaction can negatively influence several features of natural regeneration, for instance, decreasing root length and the overall biomass of the seedlings [8].

Therefore, scientific research in the sector of reduced impact logging has been focused on the development of possible solutions to limit soil disturbance related to forest operations [3,6,9]. The suggested best practices converge on the importance of carrying out forest harvesting in optimal climatic conditions or better with the soil in a situation of adequate bearing capacity, which is strictly related to soil moisture. In this framework, the application of the precision forest harvesting (PFH) approach has been showing interesting results [10]. In particular, the application of geographic information system (GIS) and global navigation satellite system (GNSS) are valuable instruments for forest harvesting planning [11–14]. Picchio et al. demonstrated, for instance, that an optimised strip road pattern developed via GIS can decrease by more than half the soil area affected by the passage of the machineries [15].

One of the most recent and interesting applications of GIS to tackle the issue of reducing soil disturbances caused by logging consists of the development of trafficability maps [16–18]. These maps are generally developed starting from a digital terrain model (DTM) and indicate areas that are expected to be particularly sensitive to soil compaction and therefore should be avoided by the operator who is driving the machine [19,20]. For the development of trafficability maps, sensitive areas are identified as the ones with high moisture content [21,22]. In fact, wet soils are more prone to soil compaction [17,23].

Therefore, trafficability maps are generally developed based on soil wetness indices, and among these, one of the most applied in the last years has been the depth-to-water (DTW) index. The depth-to-water (DTW) concept was developed and tested by Murphy et al. [24].

DTW maps have been applied and tested in a Boreal climate for the prediction of perennial streams, wet or water-saturated areas, and sensitive areas for ground-based trafficking [25–28]. These instruments are well-established in the Boreal climates and are assumed to be good predictors of soil moisture conditions [27,29].

More recently, DTW was applied to predict soil strength and areas prone to higher machinery-induced compaction in European temperate forests; however, the results were not fully satisfactory [29,30].

It is worth mentioning that DTW maps have never been applied in the context of Mediterranean forests. Instead, these instruments could be particularly useful in this zone. Coppicing interventions, which are one of the most common forest management in Italy [31,32], are carried out during the winter when soil moisture is higher. These have a subsequent lower bearing capacity, considering that soils are generally not frozen during the winter months. Therefore, the possibility of developing trafficability maps starting from the DTW index is very interesting for implementing SFOs in Mediterranean forests.

In this framework, the present study aimed to evaluate the efficiency of DTW maps in the prediction of soil-sensitive areas in oak coppice forests. A preliminary application of a DTW model was superimposed in a GIS environment on the skid trail network identified after logging activities. Then, a comparison of soil physico-chemical and biological properties (microarthropods community measured via QBS-ar index) among skid trails located in areas at low DTW index ($\leq$1) and skid trails in areas at higher DTW value (>1) was carried out. The authors thus checked the effectiveness of the DTW index for the further development of soil trafficability maps by testing the following research hypotheses: (i) the DTW index is a clear descriptor of more sensitive soil areas; (ii) the magnitude of machinery-induced disturbance in areas at low DTW value is higher than the one in zones with high DTW value.

There are two new aspects to this study. This represents the first attempt to apply DTW maps in the context of Mediterranean forests. Moreover, this study represents a critical assessment of the efficiency of DTW maps in the prediction of areas more prone to soil disturbance while taking into account the biological aspect as well.

2. Materials and Methods

2.1. Study Area

The study area is located in Castel Giorgio, a municipality in the region of Umbria in Italy (coordinates WGS84UTM33T 249968 E; 4730069 N). It consists of two different parcels belonging to a private owner. Both parcels are turkey oak (*Quercus cerris* L.) coppices with standards (Figure 1). The intervention consisted of both sub-compartments in a coppicing intervention at a growth age of 19 years, releasing 95 standards per hectare.

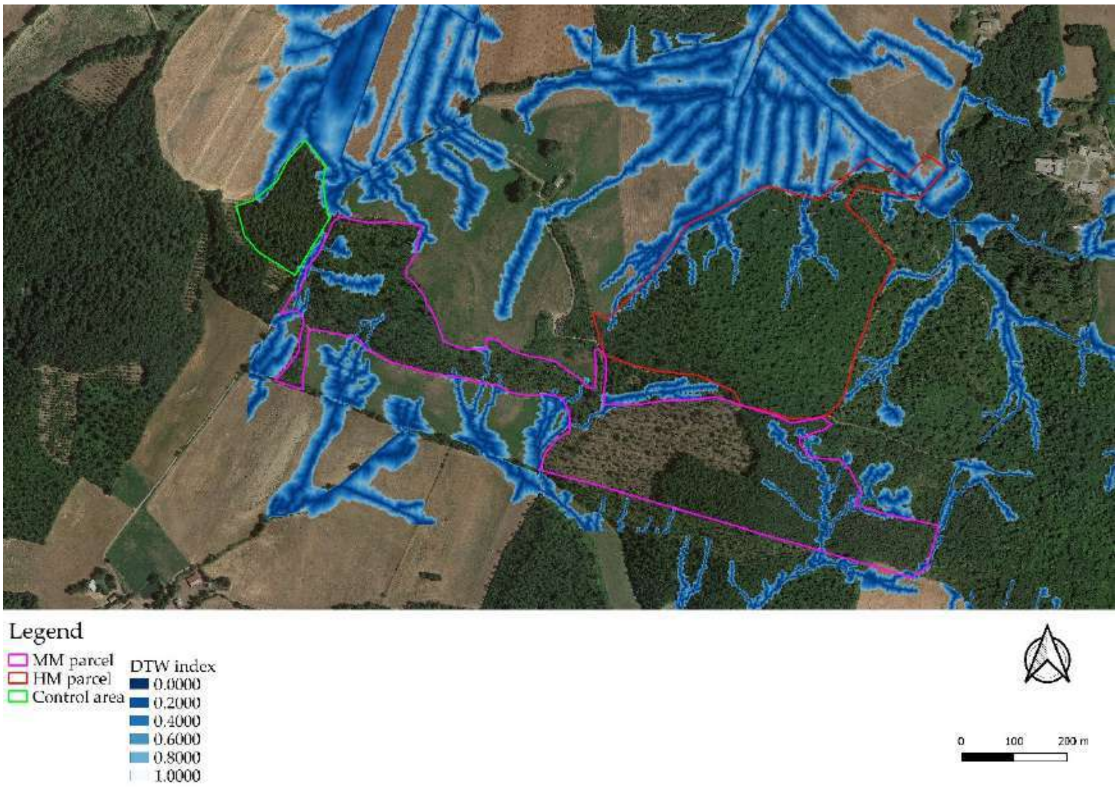

Figure 1. Google satellite image of the study area (date 7 July 2019). The boundaries of the two parcels are reported in purple (MM—medium mechanisation level) and red (HM—high mechanisation level). Control area is reported in green. Blu zones represent the areas in which DTW index is ≤1.

The two parcels (Figure 1) were harvested in two harvesting seasons, 2017 and 2019. One parcel (the one reported in red in Figure 1) was harvested with a high mechanisation level via the whole-tree harvesting system (WTS), felling operation was motor-manual with a chainsaw, and extraction was performed with a grapple skidder. The intervention surface was 16.59 ha. The other parcel (in purple in Figure 1) was harvested with a medium mechanisation level via tree length system (TLS), felling operations were done by motor-manual with chainsaw, and extraction was performed with a forestry-fitted farm tractor equipped with a winch. The intervention surface was 20.24 ha.

In both parcels, soil is volcanic with a depth ranging from 10 cm to 100 cm. According to USDA classification, it can be classified as "Typical Haplustepts fine, mixed, mesic". It consists of brown soil with an acidic sub-acidic reaction. Soil texture is the same in both parcels, and the soil can be classified as silty loam. Topographic features are also very similar in the two parcels, with limited roughness and low slope (prevalent slope 15–20%).

The overall surface of areas at a low DTW index accounted for 13% in the parcel harvested with a high mechanisation level and 11% in the one harvested with a medium level of mechanisation. Of the overall surface at a low DTW index, 6% was directly affected by machinery passage in the parcel harvested with a high mechanisation level, while this percentage was 7% in the ones harvested with a medium mechanisation level (Table 1).

Table 1. Details of areas at DTW index ≤1 in the two investigated parcels.

Parcel	Overall Surface (ha)	Surface at DTW Index ≤1 (ha)	Surface at DTW Index ≤1 Affected by Machinery Passage (ha)
High mechanisation (HM)	16.59	2.09	0.13
Medium mechanisation (MM)	20.24	2.26	0.16

2.2. DTW Map Development

The DTW index indicates the least elevation difference between surface flow channels and nearby landscape areas [33].

DTW values are zero in the zones consisting of surface flow channels. Moving upwards from flow channels in the landscape, DTW values increase, indicating decreased soil moisture away from surface waters. To develop DTW maps, therefore, it is necessary to define two thresholds: (1) flow initiation area (FIA), i.e., a catchment area required to form flow channels; (2) a DTW threshold value to consider soil as wet [34], which is generally set up as 1 [25,26]. The main advantage of DTW in comparison to other wetness indices is the function of simulating different soil moisture scenarios by changing the FIA. Indeed, small FIAs (i.e., 0.25 ha) represent high soil moisture at a site, whereas a larger FIA (i.e., 4 ha) would represent dryer conditions [17].

The DTW map was calculated from a 1 m DTM derived from LiDAR data and provided by the Italian National Geodatabase. All the procedures were implemented using the open-access software Quantum Gis 3.16, following the methodology proposed by Schönauer et al. [29].

The DTM was first processed by removing local depressions [35]. A flow direction tool was used to identify the preferential water path from each cell of the DTM. Flow channels were subsequently extracted from the DTM with a deterministic 8 (D8) flow accumulation tool [36], using an FIA value of 0.25 ha. The 0.25 ha FIA value was established to simulate the soil moisture conditions during the period in which extraction operations were carried out. This is done during the months of December–March, which is the period of time when the condition of the soil is at the highest content of moisture in the Mediterranean context.

Subsequently, the output of the flow accumulation tool was used as a starting point to calculate the shortest vertical difference between each surface grid cell and adjacent flow paths with the application of a lowest-cost function. The output raster is in the DTW index map. This map was reclassified into a binary map, assigning value "1" to all the cells with DTW index ≤1 and "0" to the other cells of the raster.

The reclassified map was uploaded on a handheld Trimble Juno GNSS receiver for the field surveys.

2.3. Experimental Design

The experimental design consisted of comparing the magnitude of disturbance to the forest soil, which occurred in areas predicted as sensitive to soil compaction by the DTW algorithm, as well as in areas that were not considered as sensitive. In both the investigated parcels, disturbed soil in the skid trails was identified within DTW-sensitive areas and non-sensitive ones. To avoid the influence of variability due to different factors, such as the number of machine passages on the skid trail, the sampling was carried out in skid trails crossing both DTW sensitive and non-sensitive areas. Thus, it can be assumed that the number of passages in those skid trails was the same in the two areas and that the presence of differences in compaction is related to different moisture conditions as predicted by the DTW algorithm. The acronyms of the different experimental treatments and the related explanation are reported in Table 2.

In each treatment, soil sampling was carried out, collecting information on the soil physico-chemical and biological parameters described in the following sub-sections. Field surveys were carried out at the beginning of March 2022 during the same period of the year in which logging activities took place. Thus, it is possible to assume that the soil moisture conditions at the moment of the field survey were comparable to the ones during logging interventions.

Table 2. Acronyms for the experimental treatments.

Acronym	Treatment
HM-DTW	Areas identified as sensitive by DTW algorithm (DTW index ≤1) in the forest parcels harvested with high mechanisation level
HM	Areas not identified as sensitive by DTW algorithm (DTW index >1) in the forest parcels harvested with high mechanisation level
MM-DTW	Areas identified as sensitive by DTW algorithm (DTW index ≤1) in the forest parcels harvested with medium mechanisation level
MM	Areas not identified as sensitive by DTW algorithm (DTW index >1) in the forest parcels harvested with medium mechanisation level
CON	Control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels

2.4. Soil Physico-Chemical Properties

Penetration resistance (MPa) and shear resistance (Mg m^{-2}) were assessed with a handheld specific instrument in the first 3–10 cm of soil. The values for the two variables referred to the soil water-holding capacity according to Saxton et al. [37]. Eighteen measurements of both penetration and shear resistance were carried out in each experimental treatment for a total of 90 samplings per feature.

Soil bulk density (g cm^{-3}) was calculated by sampling the soil via a dedicated instrument (30 soil samples in each experimental treatment). Soil samples were then put in plastic bags and sealed for shipping to the laboratory. The samples were then weighed after oven drying at 105 °C to constant weight (dry weight). The ratio between the dry weight and the volume of the cylinder of the corer (100 cm^3) gives the measure of bulk density [38]. The same samples were used to assess soil moisture.

The percentage of soil organic matter content was performed by collecting 30 soil samples in each experimental treatment. The same corer as for bulk density sampling was applied. Collected samples were put into plastic bags and taken to the laboratory.

The organic matter content was determined by incineration in a mitten at 400 °C for 4 h [38].

2.5. QBS-ar Index (Soil Biological Quality Based on Microarthropods)

The impact on the biological component of soil was evaluated by applying the QBS-ar Index. This is a qualitative index that assesses the complexity of the microarthropod community in the soil. It is based on the assumption that a higher soil quality implies a higher number of microarthropod groups which are well adapted to the soil environment.

Therefore, soil microarthropods are grouped into different biological forms taking into account their morphological adaptation to soil habitats. Each form presents a score called EMI (ecomorphological index), which ranges from 1 to 20 in proportion to the degree of adaptation [38]. The QBS-ar Index is the sum of the EMI of all the groups within the collected soil sample. To assess the QBS-ar index, 30 soil cores 100 cm^2 and 10 cm deep were collected with a specific corer in each treatment. Microarthropods were subsequently extracted from the soil with a Berlese–Tüllgren funnel. The specimens were further collected in a preserving solution (75% ethyl alcohol and 25% glycerol by volume) and identified at different taxonomic levels (class for *Myriapoda* and order for *Insecta*, *Chelicerata*, and *Crustacea*) via a stereo microscope.

2.6. Statistical Analysis

After a preliminary check of data normality with Shapiro-Wilk test [39] and homoscedasticity via the Levene test [40], the presence of statistically significant differences among the mean values of treatments was investigated via unpaired samples T-test (for soil moisture) [41] and one-way ANOVA (for bulk density, penetration resistance, shear resistance and organic matter) [42] applying HSD Tukey test as post hoc [43]. Data with non-normal distribution, or those which presented heteroscedasticity, were analysed using the non-parametric ANOVA Kruskal-Wallis test [44], applying the Duncan test [45] as a post hoc. Furthermore, non-metric multidimensional scaling (NMDS) was applied to show in a clear way the differences in the average soil parameters for the different experimental treatments. This technique is usually applied to collapse information from multiple dimensions into just a few so that they can be visualised and interpreted. The similarity measure applied was "Gower" in the form of centred axes and convex hulls as a geometric approximation. Statistical analysis was performed with Statsoft Statistica 7.0 (Statsoft, Tulsa, OK, USA) [46] and PAST software [47].

3. Results

The values of soil moisture in the experimental treatments (Table 3) showed the presence of statistically significant differences between areas with low DTW index and other areas in both parcels. In particular, in both sub-compartments, soil moisture in the areas at DTW index ≤1 resulted in being significantly higher.

Table 3. Soil moisture values referred to the different conditions analysed and results of the independent T-test analysis (HM-DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level).

Treatment	Moisture % (AVG ± SD)	t-Value	*p*-Value
HM-DTW HM	39.6 ± 2.2 35.7 ± 1.9	6.566	<0.001
MM-DTW MM	40.0 ± 3.9 32.9 ± 1.9	7.930	<0.001

Concerning soil bulk density, no statistically significant differences were detected among the mean values of the treatments (Figure 2). Therefore, soil compaction in the areas at DTW index ≤1 was not significantly different from the one obtained in the areas at higher scores of DTW index in both of the investigated forest parcels. Interestingly, there is no difference in comparison to the control area. This suggests that from three to four years after the intervention, the soil bulk density in oak coppices is fully recovered to the theoretical pre-harvesting values represented by the control zone.

Regarding penetration resistance and shear resistance, no difference was detected for both variables in the HM parcel. There are no differences between the values in HM-DTW and HM. A slight difference is, however, shown by the values of shear resistance between MM-DTW and MM, with statistically higher values in the zones with DTW index ≤1. On the other hand, no difference between MM-DTW and MM was revealed for penetration resistance. Focusing on the comparison with the control area, values of penetration resistance are fully recovered to the pre-intervention situation in HM, while there are still significant differences between the values in MM parcel and the control area. Values of shear resistance seem to be recovered to the pre-intervention situation in both parcels, except for MM-DTW (Figure 3).

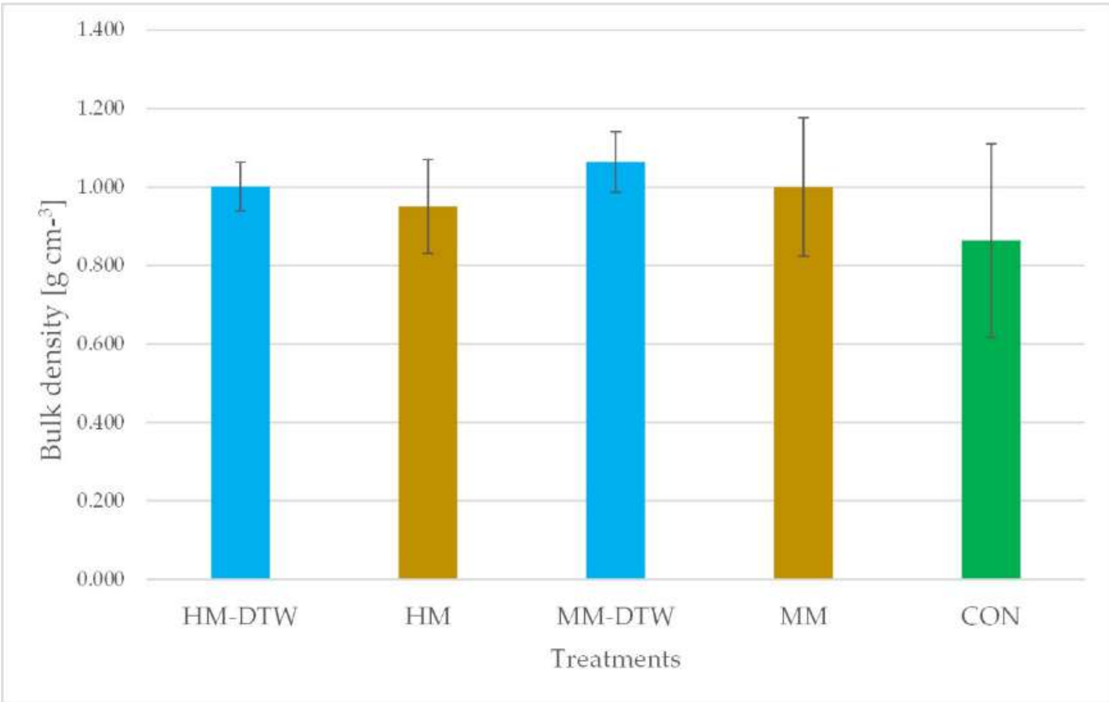

Figure 2. Bulk density for the different treatments. Obtained *p*-value from ANOVA was $p = 0.37$ (HM-DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level; CON—control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels).

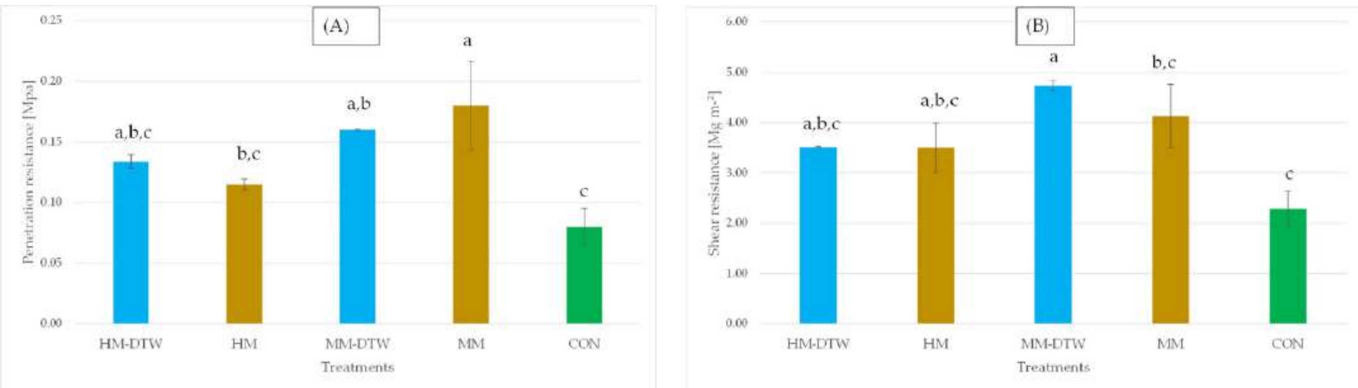

Figure 3. Penetration resistance (**A**) and shear resistance (**B**) for the different treatments. Obtained *p*-values from ANOVA were $p = 0.00041$ for penetration resistance and $p = 0.00012$ for shear resistance. Different letters indicate homogeneous groups ($p < 0.05$) according to HSD Tukey test (HM-DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level; CON—control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels). Different lowercase letters indicate different homogeneous groups at $p < 0.05$ according HSD Tukey Test.

Values of soil organic matter are not fully recovered to pre-intervention values in both parcels, as the control is still significantly higher (Figure 4). No difference in the mean values of organic matter was detected for both the investigated parcels between the zones at DTW index ≤1 and the ones at DTW index >1. Interestingly, in all the treatments affected by harvesting, the values of organic matter are statistically different from the control area. This demonstrates that this parameter was not recovered to pre-intervention values after a period of 3–4 years.

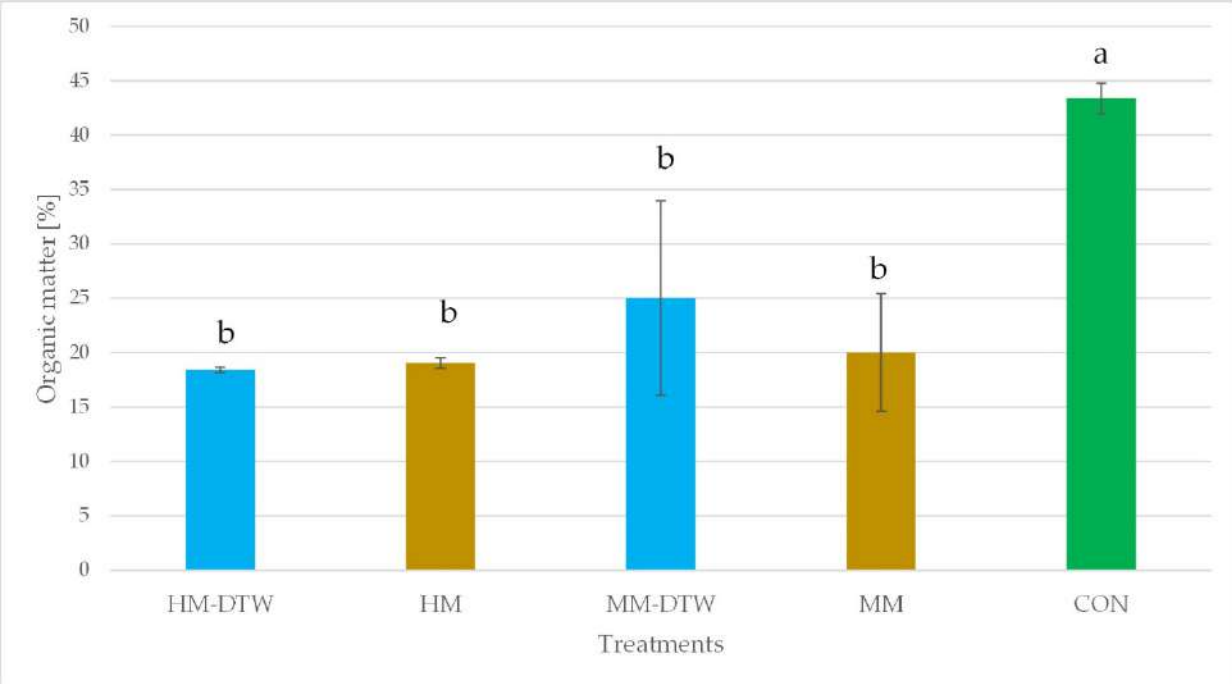

Figure 4. Organic matter for the different treatments. Obtained *p*-value from ANOVA was $p = 0.00001$. Different letters indicate homogeneous groups ($p < 0.05$) according to HSD Tukey test (HM-DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level; CON—control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels). Different lowercase letters indicate different homogeneous groups at $p < 0.05$ according HSD Tukey Test.

Interestingly, although physico-chemical variables did not show any differences between the zones at DTW index ≤1 and the ones at higher DTW index values, the biological impact seems statistically higher in the zones identified as sensitive to soil disturbance by the DTW algorithm. In fact, in both investigated parcels, the QBS-ar values in zones at DTW index ≤1 are significantly lower than the values obtained in areas at DTW index >1 (Figure 5).

Non-metric multidimensional scaling (nMDs) tests produced a two-dimensional ranking (Figure 6), which provided a significantly greater reduction in statistical stresses (i.e., the disagreement between the 2D figure obtained with nMDS and the predicted values from the regression) than expected by chance (α = 0.05). When considering bulk density (BD), penetration resistance (PR), shear resistance (SR), organic matter (OM), and QBS-ar index, the two axes explained 97.5% of the overall variance (coordinate 1 > 96%; coordinate 2 > 1%). The five variables showed the maximum correlation with the ordination axis 1. The soil condition along axis 2 was dominated mainly by OM and BD (Figure 6). The nMDS for the four disturbed scenarios showed a clear difference among the DTW areas as compared to the others, mostly in MM parcel. A clear difference is shown between HM and MM, with a greater level of disturbance in the latter case.

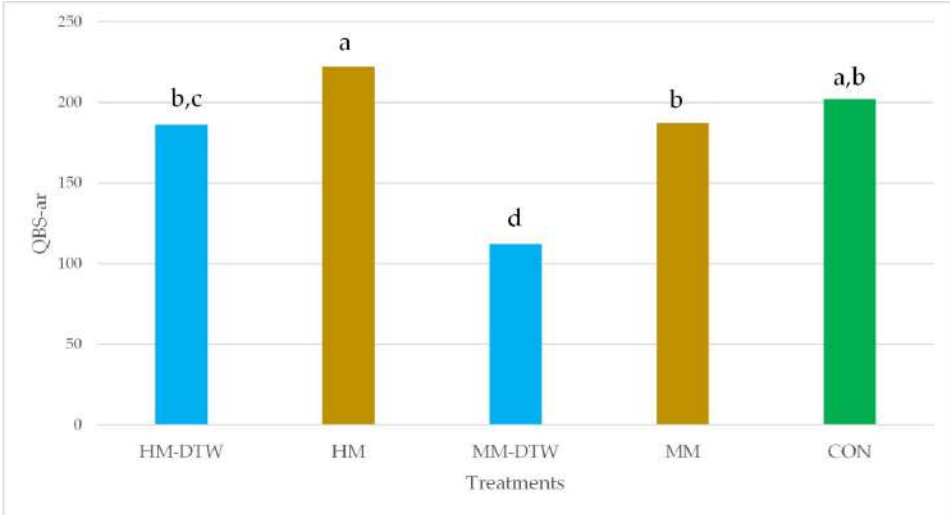

Figure 5. QBS-ar index for the different treatments. Obtained *p*-value from Kruskal–Wallis test was $p = 0.0013$. Different letters indicate homogeneous groups ($p < 0.05$) according to Duncan test (HM-DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level; CON—control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels). Different lowercase letters indicate different homogeneous groups at $p < 0.05$ according HSD Tukey Test.

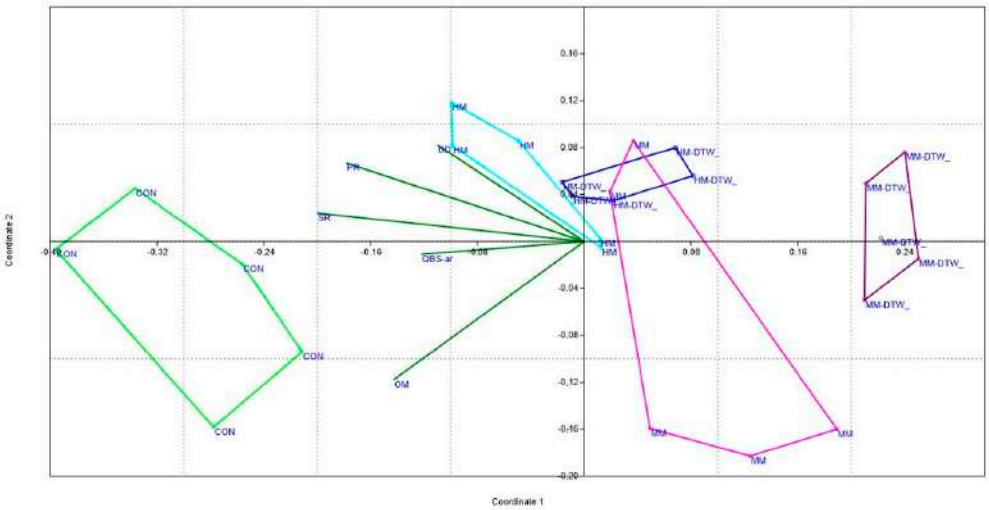

Figure 6. Non-metric multidimensional scaling (nMDS) analysis of the main indexes and indicators of the disturbed soil and the control (BD—bulk density; PR—penetration resistance; SR—shear resistance; OM—organic matter; QBS-ar—soil biological quality based on microarthropods soil biological quality) (HM-DTW—areas identified as sensitive by DTW algorithm and harvested with high mechanisation level; HM—areas not identified as sensitive by DTW algorithm and harvested with high mechanisation level; MM-DTW—areas identified as sensitive by DTW algorithm and harvested with medium mechanisation level; MM—areas not identified as sensitive by DTW algorithm and harvested with medium mechanisation level; CON—control area consisting of unharvested oak coppice in the last 20 years located close to the two parcels).

4. Discussions

This study was the first attempt to evaluate the performance of DTW maps in the Mediterranean context from this perspective. The obtained results are rather controversial but can be useful to address future research.

The DTW index has been confirmed to be a good predictor of soil moisture conditions also in the Mediterranean context. The obtained findings showed that soil moisture in zones at low DTW index had statistically significant higher moisture than the ones located in zones at DTW index >1. Therefore, from these preliminary findings, the first research hypothesis seems to be confirmed. These findings are in line with previous literature. Indeed DTW maps are considered reliable predictors of soil moisture conditions in the Boreal context [26]. In current literature accuracy of prediction is, in fact, reported to be in the range between 51% and 92% [19,24–26].

However, DTW maps did not identify soil sites particularly prone to soil compaction. The values of soil bulk density, penetration resistance, and shear resistance did not differ significantly on skid trails located in zones at a low DTW index in comparison to the values obtained in areas at higher DTW values. Therefore, soil compaction in zones at DTW index ≤ 1 was not higher than in other areas not identified as sensitive to soil disturbance, leading to the rejection of the second research hypothesis when dealing with soil physico-chemical properties. Additionally, in this case, the findings are in agreement with previous literature on the topic. A sufficient level of reliability in the prediction of soil bearing capacity via DTW maps has not been achieved yet. Indeed, recent studies failed to delineate a relationship between DTW index values and soil strength measures with different terramechanical indices, including penetration resistance [29,48]. Moreover, previous research from Ågren et al. revealed a questionable relationship between soil strength, measured via cone index, and DTW index [27].

However, in contrast with inferential statistics, the results of non-parametric statistics (nMDS) showed that soil impacts in the zones at DTW index ≤ 1 are higher than in the other areas, suggesting the need to carry out further investigation on this topic.

On the other hand, DTW maps have been shown to predict zones in which the biological impact is higher. Specifically, it can be speculated from the obtained results that in the areas at a low DTW index, the same amount of compaction led to higher disturbance to the microarthropod community of the soil. In both the investigated parcels, the values of the QBS-ar index were significantly lower in the areas at a low DTW index (HM-DTW and MM-DTW) than in the zones at DTW values > 1 (HM and MM). There may be more than one explanation for these findings, and further study is necessary. Assuming that DTW maps effectively predict zones at higher soil moisture, as confirmed by the inferential statistic applied to the obtained soil moisture data, the difference in the QBS-ar index in the soil affected by machinery passage in the areas at DTW index ≤ 1 in comparison to the other areas of the forest parcel can be related to (1) the higher moisture of the areas at a low DTW index triggers higher disturbance to soil microarthropods even if the level of compaction is the same as in other areas of the forest soil; (2) in the areas at a low DTW index there is a lower soil microarthropod biodiversity apart from the influence of logging activities.

Literature seems to indicate rather that the first explanation is probably closer to being correct. Indeed, soil moisture conditions have been identified as a major driver of the soil microarthropod community, with higher soil moisture leading to increased biodiversity of soil fauna [49–51]. Additionally, in the case of waterlogged conditions, the soil microarthropod community showed the higher variability in the presence of higher moisture content in the soil [52], but further investigation is needed to address the questions raised by the results of the present study. In each case, the obtained results can have important implications for SFM applications. The efficiency and reliability of DTW maps to identify specific areas as particularly prone to disturbance of the soil microarthropod community should be extensively applied to avoid machinery passages in these zones, limiting the impacts on soil biological properties and enhancing, therefore, the forest operations sustainability.

Indeed, uploading and displaying GIS-developed DTW maps on the onboard computers of modern forest machineries, integrated into mobile GIS applications, can provide the machine driver with site-specific information to select the extraction route, which combines consideration for both benefits for soil conservation and operational efficiency [22]. Moreover, dedicated GIS tools and methodologies can be applied to identify an optimal skid trails or strip roads network, calculated by excluding areas at DTW index ≤ 1 from the passage of the machinery [15]. The obtained results suggest another interesting finding, which is indirect because this evaluation was beyond the scope of the research, but which is however evident. This consists of the low recovery time of soil physical and biological properties after coppicing intervention in Mediterranean conditions. After a three-to-four-year period from logging, soil bulk density, penetration resistance, shear resistance, and the QBS-ar index returned almost entirely to the pre-intervention values (CON). This confirms the high resilience to soil disturbances related to logging of this kind of stand [53]. Differently, soil organic matter was not re-established. Furthermore, recovery in HM parcel seems to be stronger, confirming that the application of machineries specifically developed for forest activities, such as skidders and forwarders, can decrease the magnitude of soil disturbance [9,22].

Being this a preliminary study in the Mediterranean context, further research has to be carried out, repeating the study in different study areas with different soils and forest typologies.

In summary, however, although not able to predict areas particularly sensitive to soil compaction, DTW maps were revealed to be effective in identifying areas with higher soil moisture and, most of all, areas prone to be greatly disturbed from the biological point of view.

5. Conclusions

This study represents the first trial of applying DTW maps to identify soil areas that could be particularly prone to machinery-induced compaction in a Mediterranean context.

The obtained findings partially confirmed the research hypotheses. Indeed, DTW maps performed well in predicting soil areas with higher moisture content. On the other hand, soil physico-chemical properties in the areas identified as particularly sensitive to compaction according to DTW index did not show significant differences with other zones.

However, the most important finding of the study was that the disturbance to the soil microarthropod community in areas at a low DTW index was statistically higher than in the other zones of the parcel. More studies are needed to confirm these findings, which are potentially very important for forest management.

Author Contributions: Conceptualisation, F.L., R.V. and R.P.; methodology, F.L., R.V., D.T. and R.P.; formal analysis, F.L. and R.P.; writing—original draft preparation, F.L., R.V. and D.T.; writing—review and editing, F.L., R.V. and R.P.; supervision, R.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

Acknowledgments: The authors gratefully acknowledge the Forest Consortium of Amiata, Arcidosso, Grosseto, Italy. This research was in part carried out within the framework of the MIUR (Italian Ministry for Education, University and Research) initiative "Departments of Excellence" (Law 232/2016), WP3, which financed the Department of Agriculture and Forest Science at the University of Tuscia. This research was in part carried out within the project PLANNING CHANGE (CAMBIO PIANO), PSR 2014–2020 Tuscany Region, met. Leader. Meas. 16.2-Gal F.A.R. Maremma.

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

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8.4 Statistical Validation Of Gis-Ahp Systems For Forest Harvesting Planning. Pari, L., Cozzolino, L., Stefanoni, W., Simone, B., Lazar, S., Picchio, R., Latterini, F., Latterini, F. - (2023) European Biomass Conference and Exhibition Proceedings

Abstract: Developing the forest harvesting plan is a fundamental part of the forest planning activities which however is often not performed. Furthermore, there is the need of increasing the degree of objectivity in the selection of harvesting systems, particularly concerning extraction operation. This study properly aimed to identify in an objective way the selection criteria for the three main currently applied extraction systems (forwarder, forest winch and cable yarder) applying the AHP methodology. A survey was sent to forest experts from all the world and through the application of the algorithms of AHP the criteria with the highest influence on the choice were identified. Regarding forwarder soil bearing capacity showed to be the most important criterion, for winch it was viability density (as well as extraction distance) and for cable yarder it was the extracted timber amount. Integrating these results into GIS allows to apply the output of AHP at territorial level, developing sustainable forest harvesting plans.

Keywords: forest harvesting; GIS-AHP; MCDA; planning; sustainable management

STATISTICAL VALIDATION OF GIS-AHP SYSTEMS FOR FOREST HARVESTING PLANNING

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ABSTRACT: Developing the forest harvesting plan is a fundamental part of the forest planning activities which however is often not performed. Furthermore, there is the need of increasing the degree of objectivity in the selection of harvesting systems, particularly concerning extraction operation. This study properly aimed to identify in an objective way the selection criteria for the three main currently applied extraction systems (forwarder, forest winch and cable yarder) applying the AHP methodology. A survey was sent to forest experts from all the world and through the application of the algorithms of AHP the criteria with the highest influence on the choice were identified. Regarding forwarder soil bearing capacity showed to be the most important criterion, for winch it was viability density (as well as extraction distance) and for cable yarder it was the extracted timber amount. Integrating these results into GIS allows to apply the output of AHP at territorial level, developing sustainable forest harvesting plans.
Keywords: planning, forest harvesting, sustainable management, MCDA, GIS-AHP

1 INTRODUCTION

In the concept of utilization planning, one of the main criteria in decision-making is the logging operation. The many parameters in the choice of a logging system have a more or less important role in relation to the forest to be used [1, 2]. The variables to consider can be related to the topography of the area, to the forest intervention and to the intrinsic characteristics of the stand [3, 4]. For this reason, in this study has been developed an analysis with AHP models, i.e.: models and mathematical-statistical techniques on this operation, with three systems that are well suited to the context of Mediterranean forest being already applied or in any case near-to-practice. In detail, two ground-based systems were considered, forwarder and tractor equipped with forestry winch and an aerial system, namely a three-cables crane equipped with automatic trolley. The bibliographic analysis on the subject has made it possible to identify six variables (criteria) that have been considered in this study [1, 2, 4]. These are in particular: slope, extraction distance, soil bearing capacity, recovery, road density and accidental nature. The Analytic Hierarchy Process (AHP) is a system used to decide between possible alternatives if the decision is influenced by several variables. To obtain the importance values of the criteria through AHP, a questionnaire submitted to expert forest researchers and technicians from all over the world was used [6]. 300 compilation requests were sent to senior forest researchers and experienced forest engineers, thus obtaining the input data for AHP.

2 MATERIALS AND METHODS

To deal with complex decision-making realities where many criteria have to be considered, in the past we mainly relied on the subjectivity and ability of the individual designer [6]. Today's reality is increasingly characterized by shared choices and large information databases. From these assumptions arises the need to use support tools for designers capable of providing a complete vision of the complex design mechanisms. With these mathematical statistical tools, it is possible to decrease the subjective approach of the designer and have a much more objective comparison and analysis in sustainable times [7,8].

2.1 Multi Criteria Decision Analysis (Mcda) and Decision Support System (DSS)

Multi-criteria decision analysis (MCDA) is described by Belton and Stewart 2002 [9] as a generic term to describe a collection of formal approaches, which seek to explicitly account for multiple criteria in assisting individuals or groups in decisions that matter. In other words, MCDA manages the decision-making process in the presence of multiple criteria [10].
The MCDA methodology can be classified into four basic phases:

- structure the decision problem
- evaluate the possible impact of each alternative,
- determine the preferences (values) of decision makers,
- evaluate and compare alternatives.

To reach an optimal decision it can be useful to include multi-criteria analysis within IT tools to support the decision-making process that contain modules such as: databases, mathematical models, simulation models, business models and MCDA [6,10,11]. Systems capable of integrating these functionalities are called Decision Support Systems (DSS).

More precisely, DSS is defined as "an interactive, flexible and adaptable computer-based information system developed primarily to support the solution of unstructured decision-making"[12].

2.2 The AHP Method

The Analytic Hierarchy Process (AHP), introduced by Thomas Saaty [13], is an effective tool for dealing with complex decision-making and can help the decision-maker prioritize and make the best decision. By reducing complex decisions to a series of pairwise comparisons and then synthesizing the results, AHP helps capture both the subjective and objective aspects of a decision. In addition, the AHP incorporates a useful technique to verify the consistency of the decision-maker's assessments, thus reducing bias in the decision-making process [6].

The AHP considers a number of evaluation criteria and a number of options, among which the best decision must be made The AHP generates a weight for each evaluation criterion based on pairwise comparisons of the decision-maker's criteria. The greater the weight, the more important the corresponding criterion. Next, for each criterion, the AHP assigns a score to each option based on pairwise comparisons of the decider's options.

The higher the score, the better the performance of the option against the considered criterion. Finally, the AHP combines criteria weights and option scores, resulting in an overall score for each option and a subsequent ranking [14,15]. The overall score for a given option is a weighted sum of the scores obtained against all criteria. In the process of solving complex problems and analyzing the sensitivity of the results obtained, AHP-compatible software, Expert Choice, one of the AHP-based software, which is essentially a decision software is generally used [16, 17]. One of the advantages of Expert Choice software is that it provides graphical functionality for the user to evaluate and present the most effective results.

Researchers have also developed specific applications for the use of multi-criteria decision support in forestry, such as MPC© software [18]. The combination of GIS and hierarchical analytical process (AHP) could improve decision-making and operational priority in forestry [19, 20].

3 RESULTS AND DISCUSSION

3.1 Results and Discussion

The choice of an extraction system within the world of forest operations is a complex task, considering that the influencing parameters are multiple. Three extraction systems have been considered that are well suited to a Mediterranean forest context being already applied or in any case near-to-practice. In detail, two ground-based systems were considered, forwarder and tractor equipped with forestry winch, and an overhead system, three cable crane equipped with automatic landing gear.

The variables to be considered can be related to the topography of the area, the forest intervention to be put into practice and the intrinsic characteristics of the forest ecosystem. The analysis of the bibliography on the subject has made it possible to identify six variables (criteria) that have been considered in this study. These are in particular: slope, extraction distance, soil bearing capacity, road density and accidentality [17, 21, 22, 23].

An overview of the criteria considered and their influence on the various pillars of sustainability is presented in Table 1.

Table I: Criteria identified for the selection of the optimal extraction system.

Criterion	Acro-nym	Economy	Environ-ment	Society
Slope (%)	S	✓	✓	✓
extraction distance (m)	ED	✓	✓	✓
Soil Bearing Capacity (kPa)	SBC	✓	✓	✓
Amount of biomass (m^3 ha^{-1})	ETA	✓		
Road density (m ha^{-1})	ED	✓	✓	✓
Acciden-tality (%)	RG	✓		✓

3.2 Defining Input Data and Assigning Weights for Criteria

A special questionnaire has been developed for the retrieval and assignment of weights related to the criteria. The questionnaire is structured in three different parts, each linked to an extraction system, where forestry experts could express their knowledge on the influence of the criteria.

Example questionnaire:

In your opinion, how important is the (criterion) parameter in (extraction methodology)?

(1 absolutely not important; 9 fundamental)

It was then brought to the attention of 300 experts in the field and received 119 responses.

To use the data obtained from the questionnaires submitted to experts in the field of forest, a further table has been developed that for each parameter and extraction system assigns a range that uses different units of measurement and more suitable for the criterion in question, and its corresponding score with values ranging from one to five. The data were used for the creation of pairwise comparison matrices for each of the possible extraction systems, a fundamental step to identify the relative weights for the various criteria [24]. The relative weights express the importance of a given criterion for the choice of an extraction system. The higher the weight arising from the AHP analysis, the higher the relative importance of that criterion for the choice of the extraction system. The sum of the relative weights of the criteria for an extraction system is 1.

Another important parameter is the CR coefficient (Consistency Ratio), which indicates the consistency of the outputs obtained by AHP. If the CR value is equal to or greater than 0.1, the AHP analysis is not consistent and the relative weights are not reliable. The obtained results for each extraction method are presented in the tables below.

Table II: Relative weights and CR coefficient

Forwarder		
Criterion	**Weights**	**CR**
Slope (%)	0,143	0,0001
extraction distance (m)	0,143	
Soil Bearing Capacity (kPa)	0,286	
Amount of biomass (m^3 ha^{-1})	0,143	
Road density (m ha^{-1})	0,143	
Accidentality (%)	0,143	

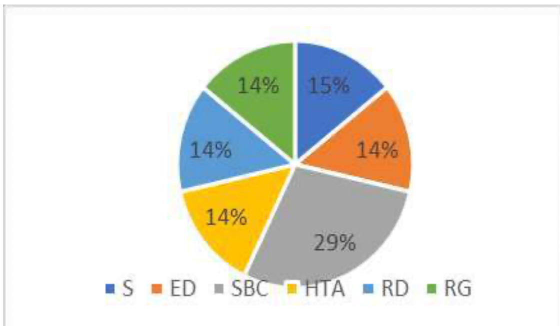

Figure 1: Chart of relative weights percentages for forwarder

Table III: relative weights and CR coefficient

Tractor equipped with forestry winch		
Criterion	**Weights**	**CR**
Slope (%)	0,136	0,0002
extraction distance (m)	0,259	
Soil Bearing Capacity (kPa)	0,136	
Amount of biomass (m^3 ha^{-1})	0,075	
Road density (m ha^{-1})	0,259	
Accidentality (%)	0,136	

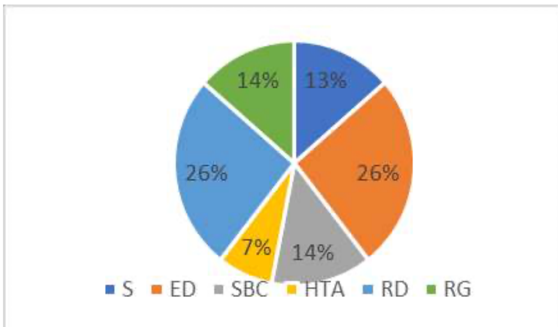

Figure 2: Chart of relative weights percentages for tractor equipped with forestry winch

Table IV: Relative weights and CR coefficient

Three cable crane equipped with automatic trolley		
Criterion	**Weights**	**CR**
Slope (%)	0,161	0,01
extraction distance (m)	0,161	
Soil Bearing Capacity (kPa)	0,06	
Amount of biomass (m^3 ha^{-1})	0,399	
Road density (m ha^{-1})	0,161	
Accidentality (%)	0,06	

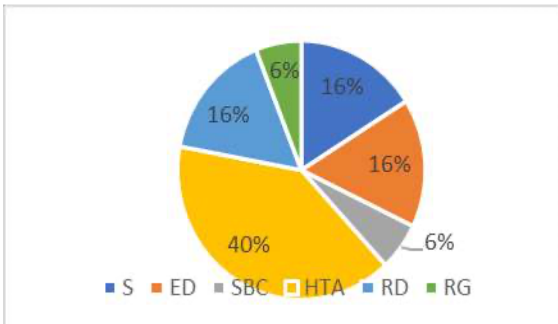

Figure 3: Chart of relative weights percentages for Three cable crane equipped with automatic trolley

4 CONCLUSION

The analysis of the extraction systems showed that:

For the forwarder, the load-bearing capacity of the soil was found to be the most important criterion in this type of extraction. This is due to the fact that the passage of heavy vehicles on soils with low load-bearing capacity can create significant impacts on the ground. At the same time, among other criteria, there were no differences in relative weights, indicating that all parameters still have an influence.

The application of the tractor with forest winch was instead considered linked to the extraction distance and road density. On the contrary, the amount of wood material has been identified as the least important criterion, underlining the suitability of this extraction system even in interventions where the quantity of wood material is limited.

The opposite is instead highlighted by the data for the choice of the cable crane. The parameters related to the morphology of the soil, such as accidentality and bearing capacity of the soil, were not considered as important in the choice. The most important criterion was identified in the amount of wood material removed.

Therefore, mathematical-statistical systems and techniques, such as AHP, allow to obtain greater objectivity in the choices, going beyond the logic of the experience of the technical designer with outputs that can be integrated into GIS systems and represent the starting point for the drafting of forest harvesting plans.

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8.5 Precision Forest Harvesting Approach In The Utilization Of Riparian Forests. Latterini, F., Stefanoni, W., Lazar, S., Pari, L., Venanzi, R., Tocci, D., Picchio, R. - (2022) European Biomass Conference and Exhibition Proceedings

Abstract

European Union is encouraging renewable energy production from biomass. Forestry sector is one of the major producers of biomass and this is particularly true for riparian forests. Such stands indeed show high biomass yield, even if the attainable assortments have low economic value, on the other hand, interventions are needed to allow for the hydrogeological safety of the area. Considering this there is a strong need to optimize forest operation in such stands, ensuring sustainable forest operation for what concerning all the three pillars of sustainability. Proper planning of forest utilization is crucial to ensure sustainable forest operation and precision forest harvesting approach, through technologies such GIS, can be a powerful instrument to reach this aim. The present study was set up in Lazio Region in Italy. The aim was to perform a preliminary planning of the forest intervention in the riparian stands comparing two different extraction systems, i.e. cable skidder and forwarder with particular reference to the occurred impacts to forest soil. Starting from the Digital Terrain Model at 10 m resolution of the area and applying the RDBM method developed and improved by the same research group, the skid trails/strip roads network needed for intervention was designed in a semi-automatic way and the results of the two simulations (one for each extraction system) were compared in terms of soil impacts. Cable skidder showed to be the most appropriate system in this kind of interventions, where working productivity is important but even more attention has to be put to limit the impacts to soil considering the high ecological and hydrogeological value of these stands. The lower working distance of forwarder indeed led to a viability density needed for the intervention of 611 m/ha while only 172 m/ha were sufficient for allowing extraction via cable skidder.

Keywords: cable skidder; forwarder; GIS; reduced-impact logging; sustainable forest operations

PRECISION FOREST HARVESTING APPROACH IN THE UTILIZATION OF RIPARIAN FORESTS

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ABSTRACT: European Union is encouraging renewable energy production from biomass. Forestry sector is one of the major producers of biomass and this is particularly true for riparian forests. Such stands indeed show high biomass yield, even if the attainable assortments have low economic value, on the other hand, interventions are needed to allow for the hydrogeological safety of the area. Considering this there is a strong need to optimize forest operation in such stands, ensuring sustainable forest operation for what concerning all the three pillars of sustainability. Proper planning of forest utilization is crucial to ensure sustainable forest operation and precision forest harvesting approach, through technologies such GIS, can be a powerful instrument to reach this aim. The present study was set up in Lazio Region in Italy. The aim was to perform a preliminary planning of the forest intervention in the riparian stands comparing two different extraction systems, i.e. cable skidder and forwarder with particular reference to the occurred impacts to forest soil. Starting from the Digital Terrain Model at 10 m resolution of the area and applying the RDBM method developed and improved by the same research group, the skid trails/strip roads network needed for intervention was designed in a semi-automatic way and the results of the two simulations (one for each extraction system) were compared in terms of soil impacts. Cable skidder showed to be the most appropriate system in this kind of interventions, where working productivity is important but even more attention has to be put to limit the impacts to soil considering the high ecological and hydrogeological value of these stands. The lower working distance of forwarder indeed led to a viability density needed for the intervention of 611 m/ha while only 172 m/ha were sufficient for allowing extraction via cable skidder.
Keywords: sustainable forest operations, reduced-impact logging, forwarder, cable skidder, GIS

1 INTRODUCTION

Forestry plays a key role in the optic of renewable energy production [1,2]. In this framework, utilization of riparian forests can provide a substantial amount of fuelwood, relying on the interventions which have to be carried out to ensure hydrological protection [3]. However, riparian forests are particular ecosystems, which can be highly susceptible to human disturbance [4].

Apart being nesting sites for several bird species [5], these forests are located on soils which can be particularly sensitive to soil compaction, as a consequence of the high moisture content [6,7]. Therefore, a proper planning of the intervention is crucial to reduce the environmental impacts of logging activities.

In this framework, the application of the precision forest harvesting approach can be an interesting solution to limit the disturbance to soil triggered by machinery traffic [8–12]. The goal of the present work was properly to perform a preliminary planning of the forest intervention in the riparian stands comparing two different extraction systems, i.e. cable skidder and forwarder with particular reference to the impacts to forest soil.

2 MATERIALS AND METHODS

Study area consists of a theoretical logging intervention on a riparian forest located in Central Italy along the course of Paglia river (Acquapendente Municipality). This represents a mere example for the application of precision forest harvesting to riparian stands. Intervention area is 11.90 ha, with prevalent slope of 4.9% and maximum slope of 15% (Figure 1).

The stand presents a complex structure, which can be described as an old coppice (50-60 years) with the presence of some big trees belonging to *Populus spp* and *Salix spp* species with the sporadic presence of turkey oak (*Quercus cerris* L.). Several individuals are in a decaying phase, and there is the presence of a large amount of deadwood which is compromising the hydraulic section of the river.

The intervention consists of a clear cut of the trees located into the river-bed, while a coppicing intervention with 60 standards per hectare is planned for a buffer of 10 m from the river-bed. Pre-intervention road density was 144 m/ha.

The applied harvesting method is WTS (whole tree system) with motor-manual felling via chainsaw. Extraction operation is instead planned both for a cable skidder and a forwarder.

Figure 1: Study area.

Planning of the needed forest road network for the two harvesting systems was carried out with the open-source GIS software Quantum GIS, version 3.16.

Starting from a DTM at 10 m resolution the accessible area to a cable skidder was calculated with the RDBM method [10], considering a working distance of 100 m, for the forwarder the considered working distance was instead 12 m. The skid trails/strip roads networks needed to extract the wooden material from all the intervention area were subsequently developed with the plugin Forest Road Designer.

3 RESULTS AND DISCUSSION

Details of the planned skid trails and strip road networks are given in Table I. As it is possible to notice, in the current situation, a cable skidder would be able to extract the wooden material from the 84% of the intervention area. With just 640 m of new skid trails the entire surface would be accessible to this machinery.

The length of strip roads needed is instead much higher. On the other hand, considering the low economic value of wood chips attainable from this kind of intervention, applying an advanced level of mechanization is the only way to achieve positive stumpage values. Therefore a proper planning of the intervention and the application of best management practices are even more important [13]. The application of forwarders for extraction allows to reach high work productivity [14,15], but the low working distance of this machinery obviously lead to a high percentage of disturbed surface [16].

Applying the precision forest harvesting approach showed to be an effective solution for the proper planning of forest road network. Moreover, thanks to the possibility of uploading the designed skid trails/strip roads patterns of the on-board computer of modern forest machineries, the operator can easily follow the optimized roads, increasing work productivity while working in safe conditions.

Table I: Detailed of the planned forest road networks.

Parameter	Cable skidder	Forwarder
Surface currently accessible (ha)	9.42	-
Surface currently accessible (%)	84	-
Adjunctive skid trails/strip roads (m)	640	5,561
Post-intervention viability density (m/ha)	172	611

4 CONCLUSION

The study confirmed the effectiveness of GNSS and GIS systems in improving forest utilization, both with cable skidder and with forwarder.

The planning implemented through GIS does not only lead to advantages in the environmental sphere, but also in the economic and social ones. By reducing the number of machine passages and optimizing the logistics, the work productivity can be increased. Furthermore, by forcing the passage of vehicles on limited slopes that can be tackled safely by the vehicle in question, a high level of work safety is guaranteed for the forest operator.

The effectiveness of Precision Forest Harvesting can therefore be affirmed as a good practice in improving forest operations regarding all three pillars of Sustainable Forest Management

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6 FUNDING

This research was funded by European Union’s Horizon 2020 project Becool grant number 744821.

7 LOGO SPACE