



Article

The Application of Two Approaches Using GIS Technology Implementation in Forest Road Network Planning in an Italian Mountain Setting

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Abstract: A well-planned forest road network is essential for meeting the goal of sustainable forest management. Forest roads play a key role in commercial purposes, fire prevention, and recreational activities. The aim of this work was to apply precision forestry in the analysis of the forest network of two forest ownerships in Tuscany. A proposal was formulated based on the information obtained regarding future forest road construction. This proposal takes into consideration technical effectiveness and environmental sustainability, with particular attention paid to low-impact logging. Two systems were tested so as to gain a better comprehension of different technical approaches. One system was reported by other researchers and the other was developed by the authors of this paper. The aim was to provide a valid instrument and possible alternative for forest managers involved in decision making. This study highlights the importance of precision forestry, even on a small-scale technical application level in forest road planning, thus helping managers and owners during the decision-making process in forestry operations.

Keywords: precision forestry; GIS (Geographical Information System); forest road; logging activities; ecosystem service; forest management

1. Introduction

Forest road network planning represents one of the major challenges in the perspective of a sustainable forest management [1–7]. In the past, the forests roads were built mainly to assist the extraction and transportation of wood and non-wood products. However, in recent decades, the increasing importance of forest multi-functionality has led to a different approach to forest road management, adding further functions and purposes to those related to wood harvesting. A road network may be used for transportation purposes of inhabitants, access to grazing lands, to improve and maintain water engineering structures, to improve wildlife habitat, for recreational activities, for natural hazard prevention and management, and for fire prevention and suppression [3–16]. Taking into account these purposes, forest road planning aims to achieve a sustainable development of a network characterized by an increased multi-functionality [8–11].

Forest road network planning, design, construction, and maintenance are costly phases necessary for developing and using forest roads in a sustainable way. The complete process related to a forest road's life is one of the costliest in forestry activities. For these reasons, its planning requires a

commercial assessment of production costs, which implies silvicultural treatments, and should consider all potential environmental impacts. On the other hand, a forest road network that is well designed and properly used and maintained has low environmental impact and facilitates the application of the best possible extraction and transportation systems, contributing considerably to sustainable forest management [17–21].

As found by many authors [22–27], there are many factors that influence sustainable forest management. The dominant factors include logging activities, felling intensity, skill of forest operators, mechanization, level of logging operation planning, site conditions and road density.

In particular, in forestry operations such as thinning or selection cutting, the road network plays an important role in reducing damage to the residual stand, minimizing soil disturbances in the area, and optimizing productivity [4,18,20,28]. For other simpler silvicultural techniques such as coppicing, clear cutting, or shelterwood, the limited level of road planning and applied logging technologies do not allow for a proper low-impact operation [29]. Several studies suggest reducing the area of soil disturbance and soil compaction by planning and designing an appropriate forest road network or temporary trails, thus reducing the needs of vehicle movement on forest ground [5,6,30–33]. Forest utilization planning, in the case of manual felling, should limit skidding vehicle movement solely on forest infrastructure network without descending/ascending into the forest stand [6,30–33]. In the case of fully mechanized felling, it should be more important to plan temporary trails and to improve specific actions to limit soil damage [5]. Suitable planning requires knowledge of the production costs of programmed silvicultural treatments [34] and of forest road networks [18]. In particular, bunching and extraction operations are important steps in the production of wood-based forest products, but they are also the main soil and stand impact factors [18–20,26,27,32,35,36]. Bunching and extraction operations may be carried out with various tools and methods, selected according to technical, economic, and environmental aspects. However, all of the methodologies need an appropriate road network: a high network density for ground-based systems, and a medium or low density for aerial systems.

To ensure low-impact logging in the area where ground-based extraction methods are applied, a good network of truck roads as well as skid roads and trails is required. Skid trails are used by skidders or forwarders that move logs from the felling site and bunching site to interior landing areas [37]. Haul roads connect skid trails and interior landings to gravel-surfaced forest roads.

This specific three-level road network (including forest roads, haul roads, and skid trails) is often developed with little planning and takes on an irregular form. On the contrary, the ongoing trend to constantly increase the size, power, and load of machines [38] makes it even more imperative to plan logging logistics to contain and limit soil disturbance and stand damages. Logging without planning, carefully developed with conventional methodologies, produces irregular skid trails that could cover 10 to over 70% of the soil surface and cause damage to 4 to 21% of standing trees after only a single harvest entry [13,18,19,39,40]. Appropriate road planning develops into two main types of skid trail networks: branching and parallel patterns. A branching skid trail pattern is planned to cross through the contour lines, and a parallel skid trail is planned in a parallel pattern following the contours [41,42].

Both the forest conservation approach and the important role of wood production have to be taken into account in the decision-making process for forestry operations, with a view to sustainable management. Within this complex frame, many approaches were developed focused on sustainable forest management, reduced impact logging, and continuous cover forestry [29,32,43]. However, none of the techniques referenced in the cited studies specifically considered road management. The assessment of the optimum road density is a key factor in helping forest engineers to develop a proper forest management plan [44,45].

For these reasons, a well-designed and well-developed road network plan must support the forest management plan to permit the best maintenance and enhancement of the road network. Forest engineers have developed a Decision Support System (DSS), using Geographical Information Systems

(GISs) to better work with road planning complexities in relation to environmental sustainability, silvicultural treatments, and logging activities [3].

These information technologies and analytical tools designed to support site-specific, economic, environmental, and sustainable decision-making for the forest sector are called “precision forestry”. The concept of the “precision approach” was translated into the forest sector in the early 2000s in the US [46,47]. Subsequently, precision forestry has rapidly gained ground in various applications such as forest inventory, management, engineering, and operations community applications. Precision forestry enables highly repeatable measurements, actions, and processes to manage and harvest forest stands, simultaneously allowing information linkages between the wood production and supply chain, as well as between resource managers and the environmental community [47,48]. In this context, it is possible to develop the concept of “precision forest operations” as a branch of precision forestry. This is a set of technologies necessary for an efficient interaction between geographical information, technical databases, and machine data logging systems. The improved information includes both higher spatial and temporal resolution of data and information, as well as access to previously unattainable information [49]. Forest operations management, therefore, needs to grasp these newly available technologies and knowledge to ensure continual improvement.

Several examples of accessibility evaluation have been developed in other studies, considering different distances in relation to the type of machines and techniques applied, and some authors refer to a relative forest openness calculation and a buffer width equal to a length of a skidder’s winch rope, reduced for the value of the mean terrain gradient [33]. Some studies set a single limit value, e.g., 300 m without slope considerations [50], or 3 km but limited to the first slope class (Max 20%) [51]. Moreover, other studies have considered different classes with varying distances, comparing buffers 150, 200, and 250 m from the road [52].

The main aim of this work was to apply a precision forestry approach to analyze the forest road network of two forest ownerships located in the region of Tuscany. Through this aim, it has been possible to define forest road improvement by taking into account technical effectiveness and environmental sustainability, with special attention paid to low-impact logging.

Two accessibility assessment systems were compared for a better comprehension of different technical approaches, one developed by Laschi et al. [3] modifying the concept of the travel time criterion (TTC) described by Hippoliti [51] and the second one with a GIS implementation of the authors, called “real distance buffer criterion” (DBC). The final scope has been to test and to develop valid instruments and possible alternatives for adequate decision making by forest managers.

2. Materials and Methods

2.1. Study Areas

The study area included two forests in Tuscany (central Italy): the forest managed by the “Macchia Faggeta company” (an association of private owners) (Figure 1) and the state forest of “Siele Selvena” (Figure 2), a public forest managed by the Union of Municipalities of Amiata and Val d’Orcia. Both areas are certified for sustainable forest management by the Programme for the Endorsement of Forest Certification schemes (PEFC). The “Macchia Faggeta” forest has a surface of 565 ha, and the “Siele Selvena” forest has a surface of about 1121 ha.

The most representative forest species in both areas are beech (*Fagus sylvatica* L.) and Turkey oak (*Quercus cerris* L.), but there are also some plantations of silver fir (*Abies alba* Mill.), Douglas-fir (*Pseudotsuga menziesii* Mirb.), black pine (*Pinus nigra* Arn.), and Norway spruce (*Picea abies* (L.) Karst).

These forests, in the past, were considered as rarely fire-prone environments, but in recent years the Amiata mountain forests have been considered as fire-prone environments. This change is mainly due to some forest fire events, strictly related to climate changes and new social and rural situations.

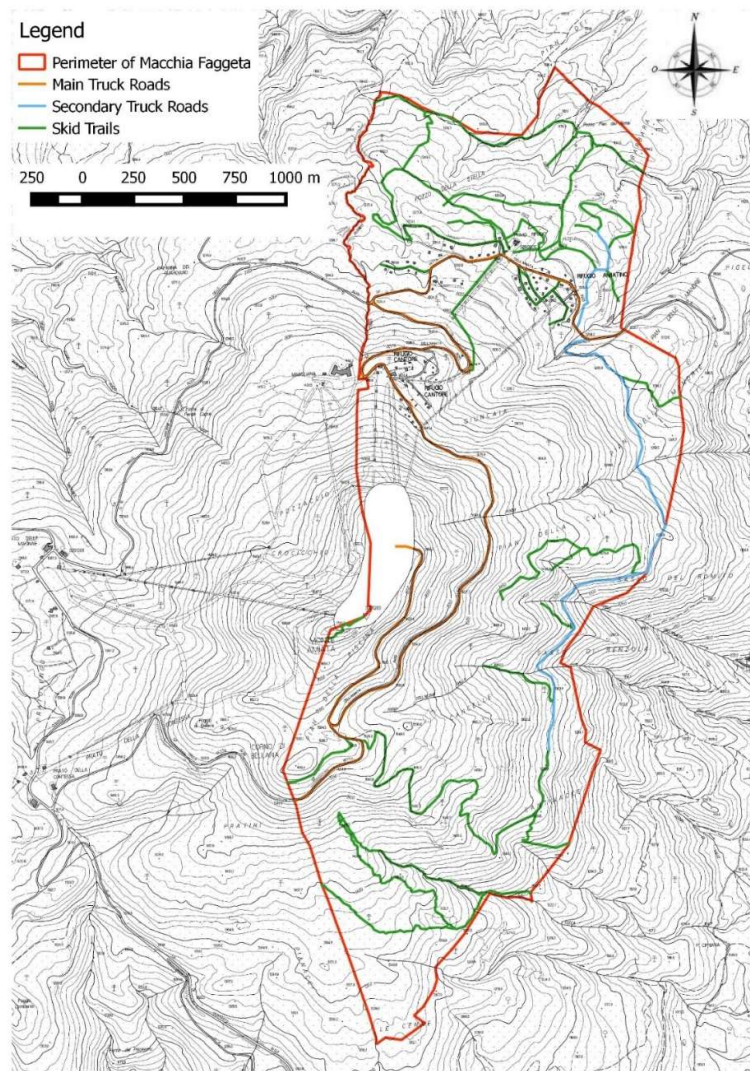


Figure 1. Traffic infrastructure network of Macchia Faggeta on a Technical Map of Tuscany Region, native scale 1:10,000.

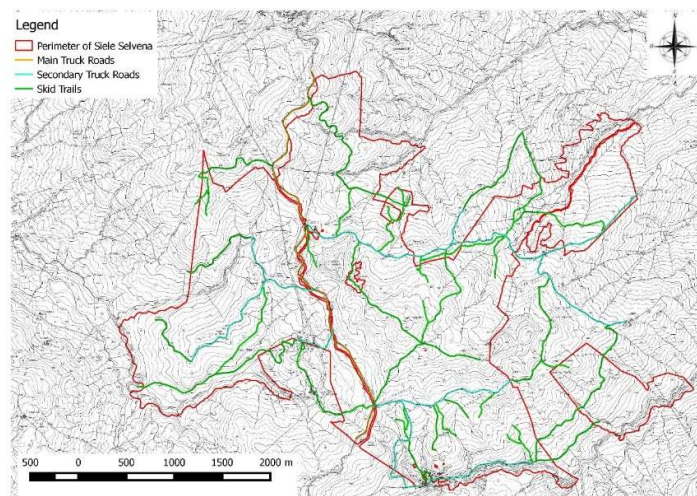


Figure 2. Traffic infrastructure network of Siele Selvena on a Technical Map of Tuscany Region, native scale 1:10,000.

2.2. Field Surveys

A complete survey of the forest road network was made in both forests (Macchia Faggeta and Siele Selvena) using an all-terrain vehicle equipped with GPS model Trimble Juno Sb with 1–2 m accuracy. During the data collection, each forest road was classified according to the classification method proposed by Hippoliti [53] (Table 1). This classification is used in Italy to determine the characteristics of machines that can be driven on a given road. Road attributes were collected by clinometer (for slope) and measuring tape (for width).

Table 1. Main road features based on classification following Italian standards as reported by Laschi et al. [3].

Features	Measurement Units	Road for Trucks		Skid Trail	
		Main	Secondary		
Width	Min	m	3.5	3.0	2.5
	Prevalent	m	5–6	4–5	3–4
Slope	Optimum	%	3–8	3–8	3–8
	Average	%	10	12	14
	Max favorable grade	%	14	18	25
	Max adverse grade	%	10	12	14
Min curvature radius in hairpin turns		m	10	7	5

* the term “max adverse grade” defines portions of forest road that forest machine (forwarder, truck, tractor and trailer, etc.) have to approach when loaded.

Information about construction characteristics and maintenance level was also collected for each forest road. According to the methodology applied by Laschi et al. [3], a survey form was filled in with the following details: coordinates and altitude of the road starting and ending points, total length, maximum and average slope, prevalent and minimum width, and minimum curvature radius of hairpin turns. For each road, a general description, an evaluation of maintenance conditions, and comments were included in the form and thus included in the dataset.

2.3. GIS Implementation and Analyses

The data collected were uploaded or digitalized on the open-source GIS software Quantum (www.qgis.org) GIS 2.12 “Lyon” in order to create a vector file of forest road network for each study area. The characteristics of each road (e.g., classification, maintenance level, width, length, etc.) were included in the attribute table. Topographic and geographic data of the study areas were also included in the GIS database. As requested for forest management plans, these data included the planning of logging activities, skid trail plans, topography of the production areas, forest road network plans, inventory information from forest management, and yearly cutting plans.

A Digital Terrain Model (DTM) with a 10-m spatial resolution [54,55] and orthophotographs were used in the geographic representation of forest roads to correct the errors in accuracy made by the portable GPS during the field survey. Orthophotographs were taken from the WMS (Web Maps Service) service of the Tuscany region.

To determine the accessibility given by the existing forest road network, in both forests two methodologies were applied: (i) the travel time criterion, described in Laschi et al. [3]; and (ii) the real distance buffer criterion, that was developed within this study. Both methodologies were based on three accessibility classes: accessible, barely accessible, and inaccessible.

2.4. The Travel Time Criterion (Ttc)

The first method was developed by Laschi et al. [3] by modifying the concept of access time, described by Hippoliti [51], based on the time required for a forest worker to make a round trip on foot from the nearest road to a given point in the forest. Hippoliti’s approach was modified in time ranges

by Laschi et al. [3] (Table 2), reducing the maximum access time to one hour for “barely accessible” areas. As reported by Laschi [3], much information is required for the GIS model implementation of this method. To obtain a “cost-map” including the information concerning the crossing time for each pixel, as suggested by Laschi et al. [3], several steps should be taken into consideration:

- slope map creation (p%), starting from the DTM, was achieved in raster format;
- the slope map was reclassified with the tool “r.reclass”. This is a tool that creates an output map layer based on an input integer raster map layer. The output map layer is a reclassification of the input map layer based on the reclass rules input to r.reclass. The reclass rules are read from standard input (i.e., from the keyboard, redirected from a file, or piped through another program). With this tool, the value 10 was assigned to all pixels with a slope up to 10; in this way, there is only one slope value for flat terrains, and the value “9999” was assigned to all pixels with a slope over 100%, assuming this value as the threshold for moving on foot;
- differential leveling (d), covered for each pixel, was calculated considering a horizontal distance (d_0) of 12.0711 m (from the average of the side of the pixel, 10 m, and the diagonal of the pixel, 14.1421 m), using the formula:

$$d = \frac{d\% \times d_0}{100} \quad (1)$$

- considering the climbing speed of 400 m_a/h (as reported in [3], “ m_a ” means absolute variation, between two points, of the difference in height respect to sea level), corresponding to 0.1 m_a/s (t_u), a raster containing information regarding the time of pixel crossing was made by the following equation (this map represents the “unit cost map”):

$$crossing\ time = \frac{d}{t_u} \quad (2)$$

- the line vector file of forest roads was converted into a points vector file;
- the r.cost full tool was applied to define the “accessible” and “barely accessible” areas, starting from the vector of road presence and the cost map previously created, and applying the time limits as maximums (15 min and 30 min for “accessible” and “barely accessible” areas, respectively). This tool determines the cumulative cost of moving to each cell on a cost surface (the input raster map) from other user-specified cell(s) whose location(s) are specified by their geographic coordinate(s). Each cell in the original cost surface map contains a category value that represents the cost of traversing that cell. r.cost produces an output raster map in which each cell contains the lowest total cost of traversing the space between each cell and the user-specified points.

Table 2. Accessibility categories used in TTC method.

Accessibility	Access Time (without Return Trip)
Accessible	15'
Barely Accessible	between 15' and 30'
Inaccessible	>30'

2.5. The Real Distance Buffer Criterion (Dbc)

This method, developed within this study, is based on the relative openness and the “working distance” of two of the most important and common extraction methods: skidding and cable yarding. The extraction methods and the “reference” were chosen considering the orographic typology, the forest characteristics, and the level of technologies used in the study areas. As a reference for the ground-based method, the Caterpillar skidder 518 C equipped with both grapple and forest winch with a rope length of 120 m (rope diameter 12 mm) was selected. As a reference for cable yarding,

the tractor-mounted Valentini V400 tower yarder was selected. The main characteristics of the reference machines are shown in Table 3.

Table 3. Characteristics of the machines.

Skidder		Cable Yarder	
Model	Caterpillar 518 C	Model	Valentini V400
Displacement (cm ³)	7000	Skyline length (m)	400
Engine power (kW)	97	Engine power (kW)	89
Mass (kg)	9700	Mass (kg)	5200
Winch Max pull (kN)	200	Power lift (kN)	30
Winch rope length (m)	120		

Taking into consideration the reference machines and previous analytical field studies on their use [21,26,39,56–59], a maximum buffer distance of 300 and 100 m from the forest road was set for the cable yarder and skidding, respectively (Table 4). Priority was given to the yarder when the distance from the road exceeded 100 m; this choice is mainly linked to the technical work capacity of forestry winches.

Table 4. Accessibility based on the DBC method.

Accessibility	Max Real Distance Buffer from Road Network (m)
Accessible to skidder	100 m
Accessible to cable-yarder	300 m
Inaccessible	>300 m

In contrast to the existing studies based on buffer zones, slope was taken into consideration, and the chosen 100 m and 300 m zone buffers are real orographic distances, i.e., the higher the slope, the lower the topographic buffer distance from the road. The steps necessary for the GIS implementation of this method are reported below:

- The DTM map was reclassified, assigning the abovementioned value of horizontal distance (12.07 m) to all pixels; this map was called “ d_0 ”;
- A slope map in degrees was created with the QGIS (Quantum GIS) tool “DEM Analysis” (Digital Elevation Model);
- With the QGIS tool “Raster Calculator” a map of cosine was created starting from the slope map in degrees. This map contains in each pixel the value of the cosine of the slope;
- With the Raster Calculator, the ratio between the “ d_0 ” map and cosine map was obtained, creating a raster in which each pixel contains a value of horizontal distance corrected according to the function of the slope; this map represents the unit cost map;
- r.cost full was applied to create the cost map;
- r.reclass was applied to the previous cost map, indicating the value “1” (accessible to winch) for values up to 100 m, “2” (accessible to cable-yarder) for values from 100 to 300 m, and “3” (inaccessible).

2.6. Forest Road Network Planning

The new forest road planning was also performed on the basis of the DBC method because in both areas assessed with this method there were forest surfaces which are inaccessible (ranging between 6% and 14%). The classification performed using the TTC method showed very limited inaccessible forest surfaces (ranging between 0.1% and 1%); in this case, it seemed that new forest road planning was not necessary. On the basis of the accessibility maps produced with the DBC method, a proposal for the

further development of the road network was put forth, thus increasing the forest accessibility in the Macchia Faggeta and Siele Selvena areas. This planning phase was developed step by step. The first step was the analysis of the “inaccessible” areas to detect the points that should be reached by new forest roads, in order to increase accessible areas. The r.drain algorithm (Quantum GIS 2.12 Lyon, 2012) was applied starting from a cumulated cost map based on slope values to define the route to connect these points. This algorithm traces a flow through a least-cost path in an elevation model. The input elevation surface (a raster map layer) might be a cumulative cost map. The output result (also a raster map layer) will show the least-cost paths between each user-provided location(s) and the minima (low category values) in the input map. This algorithm was developed for hydrogeological studies but could also be applied to viability network planning. This process is made up of several steps, listed as follows, which were repeated for each new road segment:

- Identification of the points that should be reached by the new road segment and the starting points at which the new road segment is connected to the previous existing road network;
- A cost map was created considering the slope map as the “unit cost map” and the first point of the segment as the “starting point”;
- The r.drain algorithm was used to calculate the least costly path, considering the second point as the “starting point” and the previously created cost map as input;
- The result of the r.drain algorithm was a raster that was converted into a vector file of lines and added to the previously created vector file of viability.

This methodology is very useful during the planning phase but it is important to specify that this aspect was developed only as first step of new forest road planning. For this reason, only the hillslope was considered. From this first approach, it will be possible to know when it could be necessary to build new roads and then to start with specific and more detailed planning and design of new forest roads.

2.7. Synthetic Economic Estimations for Forest Management

In order to take into consideration secondary aspects of these methodologies, stumpage value, forest earnings, and forest road building costs were calculated. For the stumpage value, the data were obtained on the basis of market analysis (20 interviews conducted by the authors with forest operators and technicians) for the final cutting of the high beech forest in the Amiata mountain (from 3000 to 5000 €/ha) and late thinning (from 1000 to 2000 €/ha). For the forest road building, particularly skid trails in the mountainous areas of central Italy, the data were obtained on the basis of intervention analysis; 20 interviews were conducted with forest managers and technicians, and the results showed that the costs ranged from 35 to 60 € m⁻¹. The main objective of this study was to test and develop valid instruments and a possible alternative for adequate decision making for forest managers through precision forestry; for this reason, marginal importance was given to the economic assessments, which have been scrupulously conducted but using synthetic estimation methodologies.

3. Results

3.1. Study Area of Macchia Faggeta

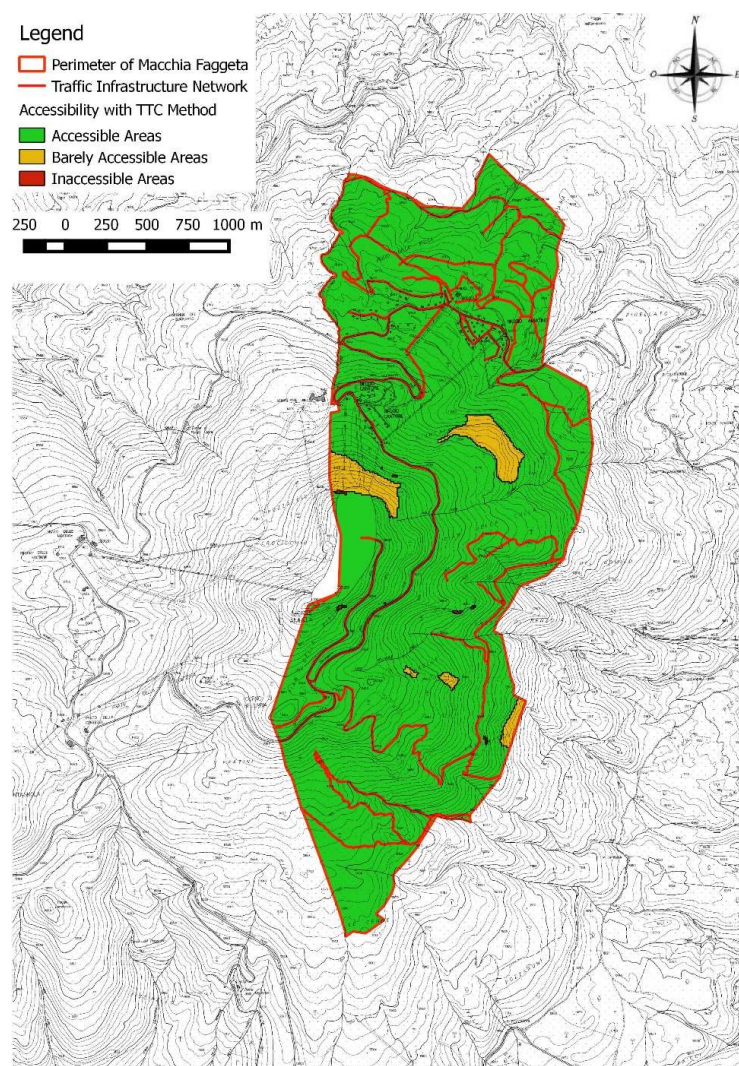
This area presents a general forest road density of 52.6 m/ha, that is composed of 13.1 m/ha of main truck roads (24.9%), 6.1 m/ha of secondary truck roads (11.6%), and 33.4 m/ha of skid trails (63.5%). From the main characteristics surveyed (Table 5), it was possible to observe how the average parameters fit within the forest road classification standards. Maintenance levels, instead, highlighted the need for small operations, above all on the secondary road network, aimed at cleaning the gutters, drainage ditches, and restoring road surfaces.

Table 5. Main forest road network features, detected during the surveys.

Road	Length (m)	Average Width (m)	Average Slope (%)	Max Slope (%)	Max Adverse Grade (%)	Min Curvature Radius in Hairpin Turns (m)
Main truck roads	7387	4.7	7%	12%	10%	11
Secondary truck roads	3452	4.2	13%	15%	11%	6.5
Skid trails	18896	2.8	15%	22%	15%	4.7

3.1.1. Travel Time Criterion

The results obtained by applying the (TTC) method showed a good accessibility level for the whole Macchia Faggeta area (Figure 3). In detail, most of the area was classified as accessible (i.e., 96.6%, 546.34 ha), and only small portion of the forest was classified as barely accessible (i.e., 3.3%, 18.7 ha). Inaccessible areas amounted to only 0.1% (0.43 ha), distributed as small random patches in the territory. The barely accessible areas were located in the management units 33B, 256 and 8, classified as protection forest areas, as well as units 4, 1, 2 and 9. Excluding the protection forest areas, the barely accessible area under active management was only 2% of the total Macchia Faggeta forest area.

**Figure 3.** Accessibility with the TCC method for Macchia Faggeta.

3.1.2. Real Distance Buffer Criterion

According to the DBC method (Figure 4), 57.5% (i.e., 325.42 ha) of the total was classified as accessible, i.e., where extraction is made by winching/skidding, and 36.1% (i.e., 204.15 ha) was classified as barely accessible, i.e., where cable yarding may be applied in extraction. The inaccessible area corresponded to 6.4% of the total surface (i.e., 35.99 ha).

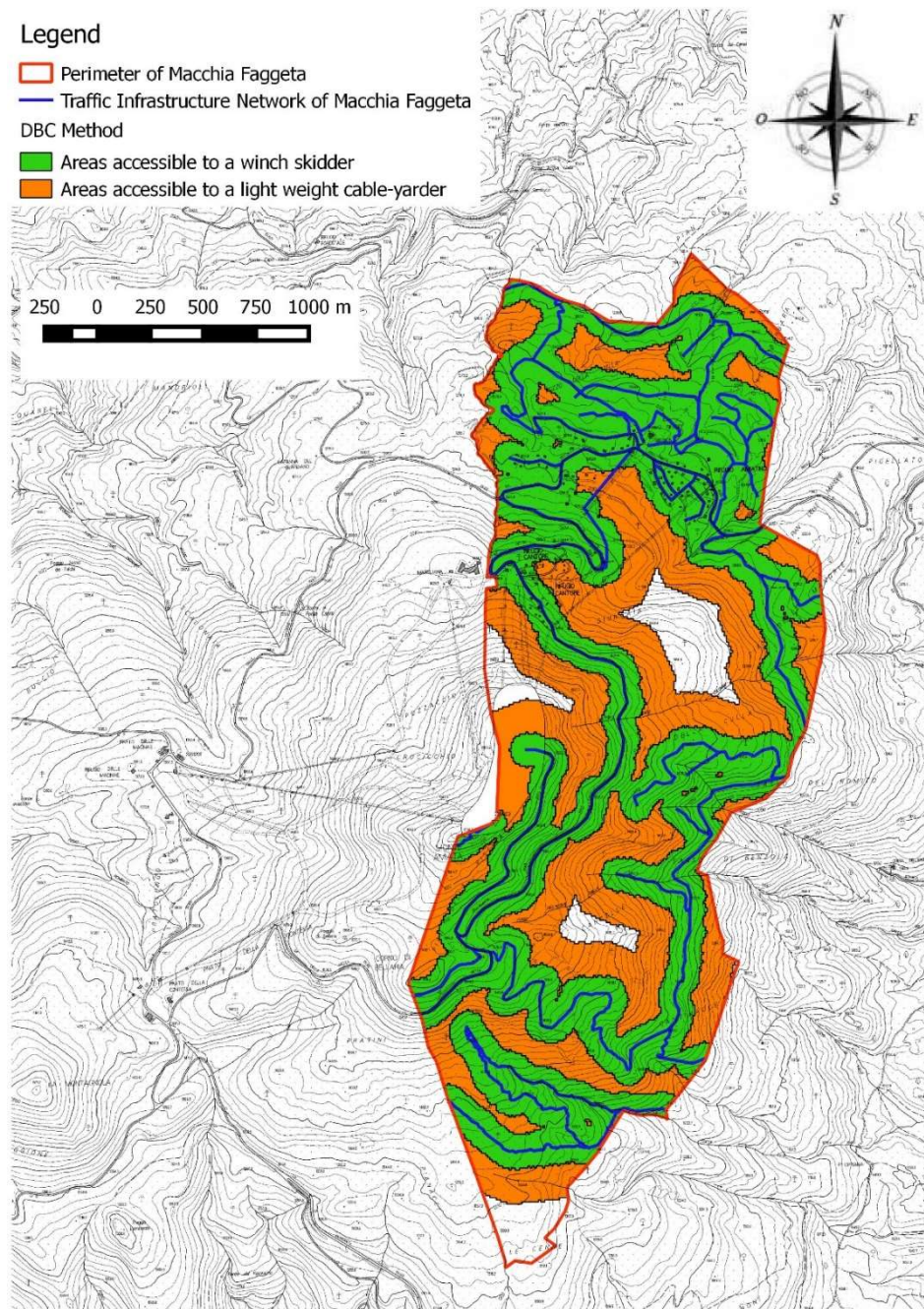


Figure 4. Accessibility with the DBC method for Macchia Faggeta.

The results showed that inaccessible areas were located in the same management units that were classified as barely accessible areas with the other method, i.e., units 33B, 256, 8, 4, 1, 2 and 9, with the addition of unit 11.

By applying the DBC method, the active management area classified as inaccessible was about 5%.

3.1.3. Proposal of Forest Road Network Improvement

As shown in Table 6 and Figure 5, based on the DBC methods, is possible to suggest the addition of 3.5 km of new road to strongly improve forest accessibility and to reduce inaccessible areas to only 1.2%, all included in the protective forest area.

Table 6. Results of the DBC method with and without additional forest road proposal for Macchia Faggeta.

	Length of Road Network	Road Density	Areas Accessible to a Winch Skidder	Areas Accessible to a Light Weight Cable-Yarder	Inaccessible Areas
Current forest road network	29.735 km	52.63 m/ha	57.5%	36.1%	6.4%
Proposed forest road network	33.278 km	58.90 m/ha	65.3%	33.5%	1.2%

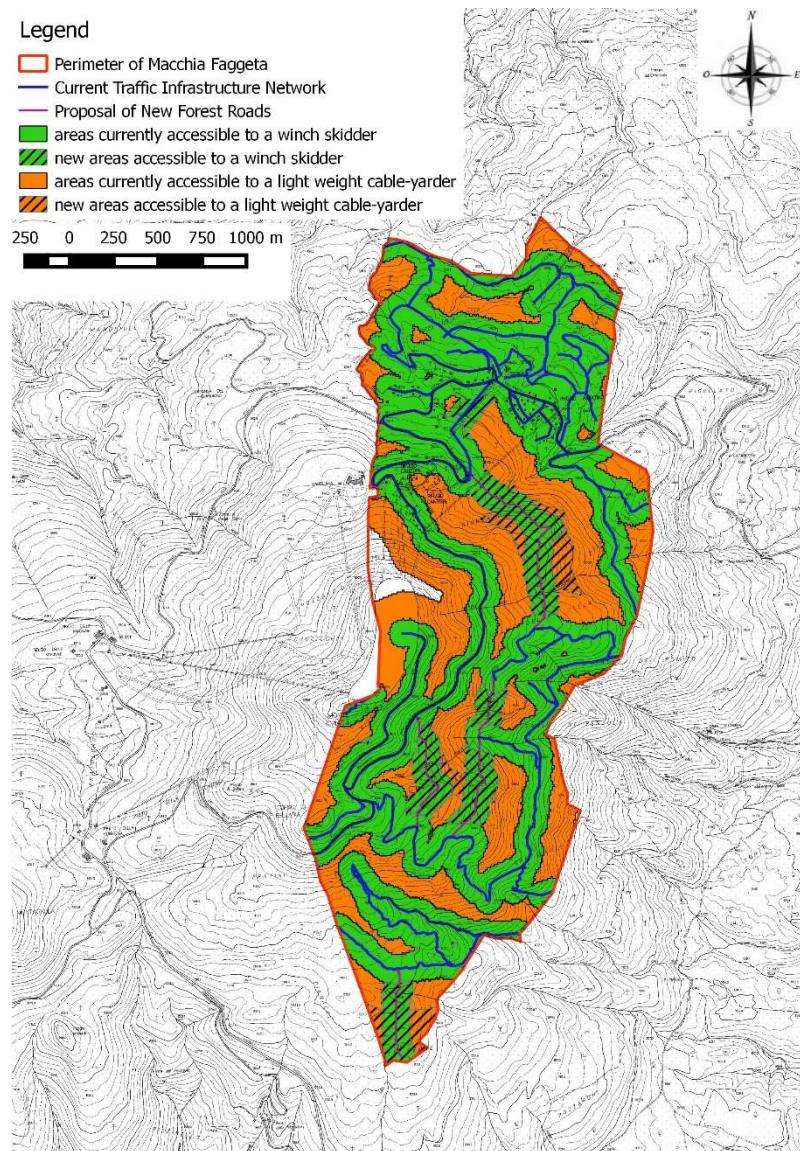


Figure 5. Accessibility with the DBC method considering the additional forest road proposal for Macchia Faggeta.

The new forest road would increase the road network by about 12%, moving from a total length of 29.7 to 33.3 km. By constructing new roads, the areas accessible to a winch skidder would increase to 65.3% while those accessible to a cable-yarder would slightly decrease to 33.5%.

3.2. Study Area of Siele Selvena

This area presents a general forest road density of 43.3 m/ha, i.e., 4.2 m/ha of main truck roads (9.7%), 11.6 m/ha of secondary truck roads (26.8%), and 27.5 m/ha of skid trails (63.5%). From the main characteristics surveyed (Table 7), it was possible to observe how the average parameters fit within the forest road classification standards. Maintenance levels highlighted the need for small operations, above all on the secondary road network, aimed at cleaning the gutters, drainage ditches, and restoring road surfaces.

Table 7. Main forest road network features, detected during the surveys.

Road	Length (m)	Average Width (m)	Average Slope (%)	Max Slope (%)	Max Reverse Slope (%)	Min Curvature Radius in Hairpin Turns (m)
Main truck roads	4671	4.9	8%	13%	9%	10
Secondary truck roads	13,055	4.4	12%	15%	10%	6.1
Skid trail	30,808	3.1	16%	21%	15%	4.9

3.2.1. Travel Time Criterion

According to the TTC method, most of the Siele Selvena forest was classified as accessible or barely accessible to forest roads (Figure 6). About 93.5% (i.e., 1049 ha) and 5.5% (i.e., 61.33 ha) of the total area were classified as accessible and barely accessible, respectively. Inaccessible areas were only about 1% (0.97 ha), mainly distributed in the northeast and southeast of the forest.

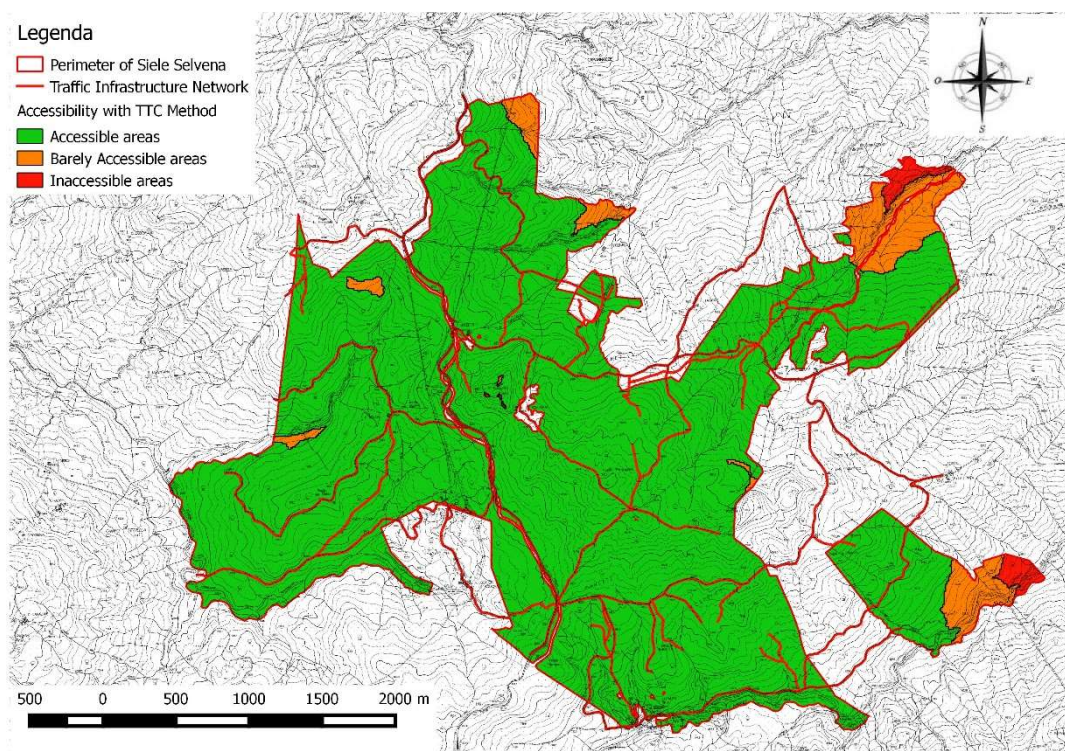


Figure 6. Accessibility with the TTC method for Siele Selvena.

3.2.2. Real Distance Buffer Criterion

According to the DBC method, the area accessed by skidders was 40.95% (i.e., 459.17 ha) of the total surface, and the area accessed by cable yarders was 44.92% (i.e., 503.63 ha) (Figure 7). The inaccessible area amounted to 14.13% (i.e., 158.39 ha).

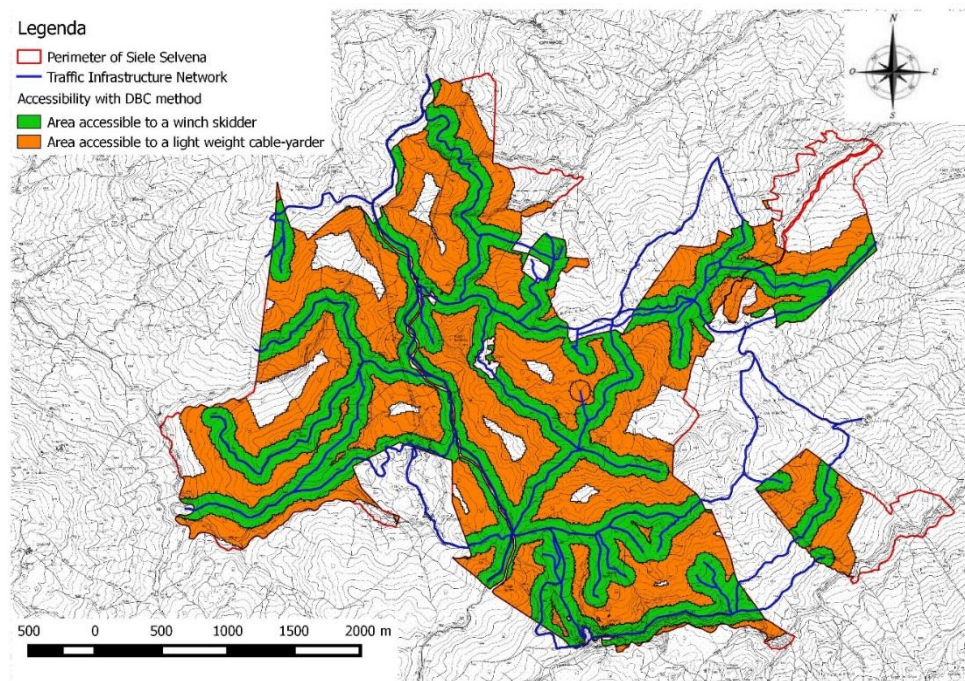


Figure 7. Accessibility with the DBC method for Siele Selvena.

3.2.3. Proposal of Forest Road Network Improvement

The results of the DBC method, shown in Table 8, highlight that with the addition of 2.6 km of new roads (Figure 8), it would be possible to reduce the inaccessible areas to 8.4%. The new forest road would correspond to 5.4% of the existing network and would increase the total length from 48.5 to 51.2 km. With these improvements, the accessible area would increase to 45.5% and the barely accessible area would reach a value of 46.03%. Further improvement of the road network would likely require very high construction costs due to the terrain characteristics and are not suggested.

Table 8. Results of the DBC method with and without the additional forest road proposal for Siele Selvena.

	Length of Road Network	Road Density	Areas Accessible to a Winch Skidder	Areas Accessible to a Cable-Yarder	Inaccessible Areas
Current forest road network	48.534 km	43.29 m/ha	40.95%	44.92%	14.13%
Proposed Forest Road Network	51.166 km	45.64 m/ha	45.55%	46.03%	8.42%

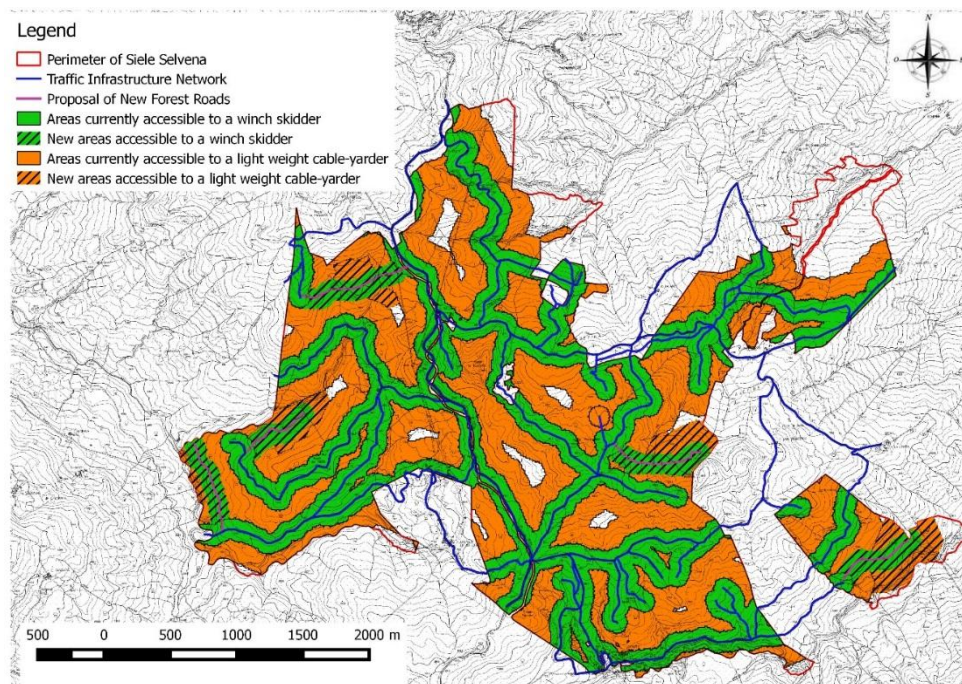


Figure 8. Accessibility with the real distance buffer criterion considering the additional forest road proposal for Siele Selvena.

4. Discussion

The results showed that both Macchia Faggeta and Siele Selvena have at present a good forest road network. As shown in Table 9, the TTC output resulted in a wider forest area classified as accessible for both Macchia Faggeta and Siele Selvena. Considering the results of TTC, all surfaces of the properties can be accessed by the forest road network. In fact, inaccessible areas classified by the TTC method corresponded to 0.1% and 1%, respectively, for Macchia Faggeta and Siele Selvena.

Table 9. Summary of the results obtained from the two methods and new forest road planning.

Description	TTC			DBC		
	Accessible Areas (%)	Barely Accessible Areas (%)	Inaccessible Areas (%)	Areas Accessible to Winch Skidder (%)	Areas Accessible to a Cable-Yarder (%)	Inaccessible Areas (%)
Macchia Faggeta current situation	96.6%	3.3%	0.1%	57.5%	36.1%	6.4%
Siele Selvena current situation	93.5%	5.5%	1.0%	40.9%	44.9%	14.1%
Macchia Faggeta with new roads	-	-	-	65.3%	33.5%	1.2%
Siele Selvena with new roads	-	-	-	45.6%	46.0%	8.4%

With the Real Distance Buffer Criterion, the areas inaccessible to winch or cable-yarder were 6.4% for Macchia Faggeta and 14.13% for Siele Selvena.

For this reason, the proposal of new forest roads was generated considering only the results of the DBC analysis.

The differences between the two methods are mainly linked to the fact that the TTC method is more general and does not take into account the problems related to timber extraction, i.e., it does not consider the economic and functional limitations of the given territory in relation to the most common extraction methods applied in the area. On the contrary, the DBC method is based on the extraction

methods actually applied in the study area, allowing us to highlight the real difficulties of carrying out a sustainable forest operation.

Winching/skidding and cable yarding are already established processes in the study area, and the operators and engineers are well trained. The result is that forest areas considered accessible by the TTC method often cannot be harvested with the available technologies, or they are harvested by crossing the limits of economic and environmental sustainability [39,40]. The DBC method instead is based on a more specific approach with respect to various harvesting systems, technologies and its limitations—notwithstanding the fact that in this method both properties were also considered in large part to be accessed by forest roads. This method gives valuable information regarding possible improvement of the forest traffic infrastructure network. It is important to underline that even if the proposed road network improvement is based on a forest harvesting approach, such an improvement may also lead to benefits in relation to environmental (e.g., firefighting and prevention) and social aspects (e.g., tourism, worker safety).

According to the DBC method, the improved forest road network will allow the extraction of timber by skidding on a good percentage of the surface, and by cable-yarder on the remaining percentage. The use of these extraction methods meets the goal of sustainable forest operation because these two methods (if correctly applied) allow good productivity while reducing the impact on soil and the residual stand by confining the forest machines to the forest road network.

Before showing the results of this work and arriving at conclusions about the DBC method, two check methods were applied. The analytical method consisted of travelling all forest roads by means of an ATV (All Terrain Vehicle) vehicle and systematically checking the correspondence between the DBC method calculation and real situation using GPS and a measuring tape (one control point every 1 km). The participatory method consisted of consulting both the Forest Managers and the forest engineers of the two properties to discuss the results with them.

The analytical method showed a positive result (percentage error < 5%). The participatory method showed correspondence between modeled inaccessible areas and real inaccessible ones, as the personnel involved in the check were satisfied with the results of the DBC calculation. In particular, they were very surprised by the new developments of the precision forestry related to logging activities and forest road survey and planning.

However, in the current situation of Macchia Faggeta, about 36 ha of the forest surface are not accessible to a winch skidder or a cable-yarder. Seven hectares of this surface are high protection forest stands, but the remaining 29 ha are high production stands. Even if these 29 ha represent only 5% of the total forest area, they are considered a loss of earnings for the manager, ranging from 94,000 to € 145,000 per harvesting cycle (data obtained on the basis of market analysis for the stumpage value of a high beech forest in the Amiata mountain). Based on the market analysis for building forest trails in mountainous areas of central Italy, the costs range from 35 € to 60 € m⁻¹. According to the data shown in Table 6, it is possible to estimate the costs of forest road network implementation. The cost of about 3.6 km of new trails ranges from 126,000 to € 216,000. The implementation of a forest road network also has a positive influence on the stumpage value of some of the closest management units (a surface of about 75 ha) for an estimable earning increase of about 8%, with a value ranging from 19,500 to € 30,000 per harvesting cycle.

For the current situation of Siele Selvena, about 158 ha of forest surface are not accessed by a winch skidder or cable-yarder. This surface is located randomly over the entire property, mainly in coppices of Turkey oak and in high forests of Turkey oak and black pine. Considering the project proposal (Table 8) of new forest roads, the addition of about 5% of new roads would lead to significantly reduced inaccessible areas, even if about 94 ha remain inaccessible to a skidder winch or a cable-yarder. However, a further addition of forest roads is not recommended due to the morphology of inaccessible zones. These 64 ha represent about 6% of the total forest area. They can be considered as lost earnings for the manager, ranging between € 64,000 and € 130,000 per harvesting cycle. According to the data shown in Table 8, it is possible to estimate the costs of forest road network implementation. For about

2.6 km of new trails, the cost ranges from 92,000 to € 158,000. The implementation of a forest road network also has a positive influence on the stumpage value of some of the closest management units (a surface of about 125 ha) for an estimable earning increase of about 5%, with a value ranging from 6000 to € 13,000 per harvesting cycle.

Considering the multi-functionality of the forest road network and its multi-temporal purposes, the implementation of the costs suggested by this planning seems well-justified and sustainable. In particular, some new aspects of the multi-functionality are closely related to sports tourism, downhill activities, mountain bike, trekking, orienteering, and trail running, activities with a good economic chain. Although a higher amount of extracted wood from a single crop cycle is likely, it is improbable that the cost of road construction will be compensated for only by increased timber production. This study highlights the importance of precision forestry even on a small-scale technical application level in forest road planning. It is intended to help managers and owners in the decision-making process concerning forestry operations. However, it has to be considered that the study area presents orographic conditions and regional regulations that allow forest road construction and maintenance, whereas the situation could be rather different in countries with different approaches to road network planning, or ecological and forest management.

The importance of adequate forest road planning, in particular of skid trails, is also closely linked to environmental protection aspects (soil, tree seedlings, and residual stands), as shown in other studies on sustainable forest management assessing indicators of forest ecosystem health [16,60]. In this research [16,60], different treatments were applied in Alpine high forests near Tarvisio. A comparison between one traditional system and two innovative systems was made. The differences among the systems were related to the silvicultural treatments and the forest road network planning. The results showed a decrease in damaged trees from logging activities for the treatments with skid trail planning (without skid trail planning, 6% of trees were damaged; with skid trail planning, 0–3% of trees were damaged).

5. Conclusions

The main aim of this work was to apply a precision forestry approach to analyze the forest road network of two forest ownerships located in the region of Tuscany. The results of this analysis were used to define forest road improvement by taking into account technical effectiveness and environmental sustainability, with special attention paid to low-impact logging. Two accessibility assessment systems were compared for a better comprehension of different technical approaches. The final scope has been to test and develop a valid instrument and possible alternative for adequate decision making by forest managers.

The travel time criterion showed that almost all forest surface for both areas were accessible or barely accessible by forest roads. Unfortunately, this concept of accessibility is not always feasible in a practical way because the various technological factors have economic and functional limitations.

The method described in this paper is based on the concept of a real distance buffer. It suggests that something can be done to improve the forest network. This is very important in a vision of sustainable forest operation because adequate road planning (if correctly applied) allows managers to obtain good productivity while limiting the impact on soil and residual stands. An immediate economic approach of the forest manager leads to a short-term negative economic balance. Considering the multi-functionality of the forest road network (ecosystem services) and its multi-temporal purposes, the implementation costs of the real distance buffer approach criterion allow for planning that follows the criteria of sustainable forest management.

This study highlights the importance of precision forestry even on a small-scale technical application level in forest road planning, thus helping managers and owners in the decision-making processes concerning forestry operations.

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