DIPARTIMENTO TERRITORIO E SISTEMI AGRO-FORESTALI

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Support tools for planning and management of a forest road network

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"Per ogni presenza umana nell'ambiente di montagna che non sia per lavoro, studio o sorveglianza,
bisognerebbe fermare gli automezzi dove arrivano i servizi pubblici.
Poi tutti a piedi:
chi ha passione vera camminerà,
gli altri si fermeranno al bordo del bosco,
che è sì bene di tutti ma non da tutti"

MARIO RIGONI STERN

"For every human presence in the mountain that is not for work, study or surveillance
vehicles should be stopped where get public services.
Then all by walk:
who has real passion will walk,
the others will stop at the edge of the forest,
that is a good of everyone but not for everyone"

MARIO RIGONI STERN

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Prefazione - Preface

IT - nella presente tesi verrà presentato un esempio di come la pianificazione della viabilità forestale possa essere migliorata utilizzando le tecnologie oggi disponibili a supporto alla gestione territoriale.
In ciascun capitolo verrà presentato un strumento di supporto alla pianificazione della viabilità forestale. In questo senso ciascun capitolo può essere letto come un elemento indipendente e, al tempo stesso, continuazione del capitolo precedente e base per la comprensione del successivo.
Il percorso seguito parte quindi dalla realizzazione di uno strumento con finalità prevalentemente conoscitive, quale è l'inventario della viabilità forestale della Regione Veneto fino all'utilizzo dello strato informativo acquisito come input per lo sviluppo di modelli e metodologie finalizzate a supportare le scelte di pianificazione.
Come allegato sono inoltre riportati, sotto forma di contributi scientifici, quattro studi pubblicati durante il Dottorato di Ricerca frutto dell'applicazione sperimentale delle metodologie sviluppate e dell'utilizzo dei dati acquisiti.
La finalità principale di questa tesi è quindi quella di colmare una lacuna conoscitiva e metodologica attualmente presente, con l'auspicio che i temi, le idee trattate e gli strumenti sviluppati possano venire effettivamente utilizzati da parte dei soggetti preposti per il miglioramento della gestione della viabilità forestale.

EN - this thesis represents an example of how the management of a forest road network can be improved using new technologies to support management decisions.
In each chapter, a tool will be presented to support the management of forest roads. With this, each chapter can be read as an independent element that will support specific management needs, but at the same time it will use as baseline developments from the previous chapter and will represent the basis to better understand subsequent chapters.
The first step will be the creation of the inventory of forest road for the Veneto Region. The acquired informative layer will be used as input for the development of models, specifically designed to support the planning choices.
At the end of the thesis, attachments are also reported with four scientific articles, carried out during PhD studies, with the purpose of acquiring useful information to its development or as result of the application of the developed methodology and the acquired data.
The main purpose of this thesis is therefore to improve the management of the forest road network within the investigated area, trusting that the themes, the ideas and the tools developed will be effectively used by the management authorities and others stakeholders.

Marco Pellegrini

Abstract

Forest roads represent a strategic component for the socio-economic development of the populations living in mountainous and hilly areas. Adequate forest road networks are considered essential to exercise a rational and economic management of forests, mountain pastures and agricultural lands.
On the other hand, one must take into consideration that the presence of a road into the forest as well as poor forest road management can have many impacts on the surrounding environment.
The correct planning and management strategies are thus fundamental in order to minimize negative impacts due to the presence of forest roads while at the same time satisfying the accessibility needs of the territory.
In this thesis, a series of tools have been created to support the management of the existing forest road networks.
Firstly, the thesis will present the methodology used to create a geographic database which contains all the sections of roads within the mountainous area of Veneto Region. To achieve this objective, the latest technologies have been used both to gather information by GPS instruments, in order to manage and data-process using spatial information management software (GIS).
Using the information contained in the new informative layer, the extension and the characteristic of the regional forest roads system has been estimated and a series of indexes to evaluate the presence of forest roads at a municipality level that can be used to rank projects in founding sharing decision have been calculated.
The second part regards the development of three GIS-based decision support tools that use in an effective way the data contained in the geo-database, moving from an informative use to an operative one through data elaboration. The models have been built on a GIS environment with the Arc-GIS Model-Builder.
The first model (FORACCESS) evaluates the accessibility of the territory based on determining the time that an operator takes to reach a determined point in the forest starting from the road-side and considering the geo-morphologic characteristics of the terrain. The result can be used to define the areas where the construction of new forest roads is more needed.
Second model (FORSE) produces a map representing the feasible working area for each wood extraction system, considering the geo-morphologic characteristics of the terrain and the condition of the present road network. The result can be used for example to analyze the effects of the construction of a new road in the execution of forest operation.
The third model (ROADGRAD) evaluates the vertical gradient of the forest roads based on the digital terrain model (DTM). The resulted map contains fundamental information of the road that can be used to determine the presence of limiting point for the transit or to evaluate the needs of drainage structures.
In the last part of the thesis a methodology will be presented, using Analytic Hierarchy Process (AHP) and GIS software, to rank the maintenance priority according to the actual condition and the actual needs of a forest road network.
The use of integrated GIS tools and AHP analysis showed that different aspects related to the forest road network presence can be effectively integrated. Consequently, the approach could be used to improve the effective administration and management of maintenance planning, especially considering that existing forest road systems need to evolve toward a paradigm where other benefits (e.g. recreational value) and priorities (e.g. environmental aspects) are included.

Riassunto

La viabilità agro-silvo-pastorale rappresenta un elemento fondamentale per lo sviluppo socio-economico delle aree montane e collinari. Un adeguata presenza di viabilità è infatti essenziale per poter esercitare una razionale ed economica gestione del territorio e delle sue risorse. Và tuttavia considerato che la presenza di una strada porta con sé anche una serie di effetti negativi sull'ambiente circostante.
Per questa ragione è molto importante adottare una corretta strategia di gestione e pianificazione della rete viabile, in modo da minimizzarne gli impatti negativi e da soddisfare, al contempo, le esigenze di accessibilità del territorio.
Nel presente lavoro saranno sviluppati una serie di strumenti di supporto alla gestione della viabilità agro-silvo-pastorale.
Sarà dapprima presentata la metodologia usata per la creazione del database geografico rappresentativo della viabilità forestale all'interno dell'area montana della Regione Veneto, in quanto un'adeguata conoscenza della rete viabile rappresenta il presupposto fondamentale per la sua corretta gestione.
Nella predisposizione del nuovo strato informativo relativo alla viabilità forestale sono stati utilizzati sistemi GPS per il rilievo e strumenti GIS per l'organizzazione, la gestione e l'analisi delle informazioni.
Utilizzando i dati contenuti nel *geo-database* sono state successivamente analizzate l'estensione e le caratteristiche della viabilità forestale a livello regionale e sono stati calcolati una serie di indici per valutarne la dotazione a livello comunale e di Comunità Montana.
La seconda parte della tesi riguarda lo sviluppo di tre strumenti GIS che utilizzando i dati contenuti nel geo-database permettono di elaborare delle mappe da utilizzare a supporto delle scelte di gestione.
Il primo modello (FORACCESS) valuta il livello di accessibilità del territorio calcolando il tempo impiegato da un operatore per raggiungere un determinato punto partendo dalla più vicina strada forestale, considerando le condizioni morfologiche del terreno. Il risultato può quindi essere utilizzato per l'individuazione di massima delle aree che maggiormente necessitano della costruzione di nuove strade forestali.
Il secondo modello (FORSE) valuta le aree in cui una determinata tecnica di esbosco risulta più adatta, in relazione alla morfologia del terreno. La mappa risultante può essere quindi utilizzata per valutare gli effetti della costruzione di una nuova strada sulle tecniche di esbosco applicabili.
Il terzo modello (ROADGRAD) calcola la pendenza delle strade forestali, sulla base del modello digitale del terreno. Il risultato rappresenta un informazione molto importante che può essere usata sia per valutare l'eventuale presenza di punti limitanti al transito sia per valutare l'esigenza di adeguati sistemi di smaltimento delle acque sulle strade.
Nell'ultimo capitolo viene infine presentata una metodologia per la valutazione delle priorità di manutenzione della viabilità forestale utilizzando una tecnica di analisi multi-criteriale (AHP) che considera i benefici e i rischi connessi con la presenza della rete stradale.
L'utilizzo integrato dell'analisi AHP e di un software GIS si è dimostrato un valido strumento per l'integrazione dei molteplici aspetti coinvolti nella presenza della viabilità forestale e il conseguente miglioramento delle attuali strategie di gestione e manutenzione.

Chapter 1: Introduction

1.1. The importance of mountain forest road network

"Few forces have been more influential in modifying the earth than transportation" (Ullman, 1956). Haggett, (1965) pointed out the correlation between transportation network expansion and economic development of regions.

Forest road networks represent a strategic component for the socio-economic development of the populations living in mountainous and hilly areas. Adequate rural-forest road networks are considered essential to exercise a rational and economic management of forests, mountain pastures and agricultural lands (Cielo e Gottero, 2004).

In forest stands with a deficiency or absence of roads, it can be problematic or even impossible to complete the silvicultural operations necessary for the correct conservation of the forest, particularly with a sufficient level of rationality and cost-effectiveness. In particular, good road density has a fundamental role in forest management oriented toward less intensive interventions such as in the Italian Alps. In this type of interventions, with small amount of timber and small cutting areas, economic feasibility can only be reached through easy accessibility.

For the pastoral districts, absence or inadequacy of access can result in complications for moving the vehicles, machinery and goods needed for the work and consequentially increased difficulties in management and risk of subsequent abandonment.

The ability to easily access an area creates many different possibilities for activities (grazing, agriculture, mining etc) for the local communities.

Again a good forest road network is fundamental to guarantee access to the operators and the machines that operate in the forest fire prevention and suppression (Calvani et al. 1999).

Forest roads are also important to encourage tourists and sports activities. The roads can be preferential paths for walking, biking or skiing (Cielo et al., 2003) or guaranteed access to historical sites.

On the other hand, one must take into consideration that the work required to construct a road into the forest as well as that its unfounded management can cause many impacts to the surrounding environment. For this reason, the presence of a forest road is not always the solution to problems concerning the safeguarding and the development of the mountainous areas.

What emerges is thus a picture in which the functions of the forest roads are much diversified. This multi-functionality has been further accentuated in recent years and together with the increasing attention toward environmental problems, the management and maintenance of these system becomes particularly complex.

1.2. Cost and benefit of forest road

The presence of a rural-forest road creates many changes to the surrounding territory and environment. The uses and benefits related to this infrastructure have already been introduced and relate mainly to easy access into nature both for recreational and management purposes. The presence of a forest road has a consistent impact in lowering the extraction and transportation costs for timber production, determining often the economic feasibility of the wood utilization. The opposite factor to consider is the cost of the construction and the maintenance of the road.

On the other hand, many undesirable consequences are related to the presence of a road, both the biotic and abiotic components. Reviews about the negative effects of forest roads are present in literature (Coffin, 2007, Forman and Alexander, 1998, Marchi and Spinelli, 1997).
Figure 1 (USDA, 1999) represents a clear summary of the elements involved with the presence of a forest road.

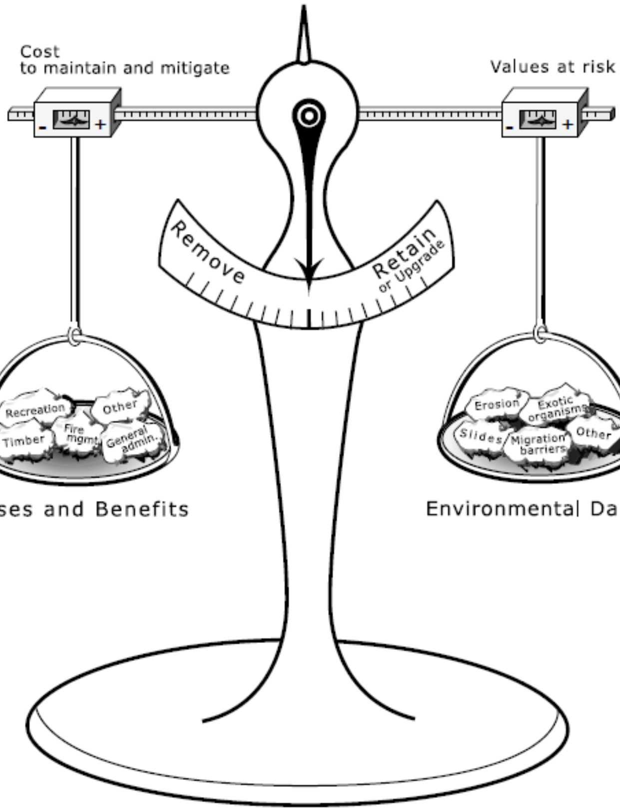


Figure 1 - Balance between all factors involved in forest road management (USDA, 1999)

The most common negative effects on the a-biotic component involve the modification of the hydrology and water quality and the consequent increase of sedimentation and erosion processes. Literature showed that the presence of a road can substantially alter natural hill slope hydrologic and geomorphic processes. It has been shown that forest roads are associated with accelerated erosion and can be a major source of sediment delivery to streams, which can degrade aquatic habitat (Forman and Alexander, 1998; Gucinski et al., 2001).
Roads are often indicated as a source of chemical pollutants, both introduced from vehicles associated with the road components and the road material itself (Grant et al., 2003).
Roads are sources of mortality and barriers to animal movement creating a fragmentation of the habitat. The phenomenon of population fragmentation has been noted across many taxon, affecting small mammals (Oxley et al., 1974), large mammals (Nellemann et al., 2001), insects (Bhattacharya et al., 2003) and herpetofauna (Smith et al., 2005).
Other effects to the landscape include the direct loss of habitat through the transformation of existing land covers and road-induced land use and land cover change (Angelsen and Kaimowitz, 1999).
Finally, negative effects are connected with the consequential presence of humans and their behavior (trash dumping, fire, illegal hunting) (Gucinski et al., 2001).

Most of these impacts occur during initial road construction, followed by decreasing impacts as roadside vegetation and surfacing mature. Also periodic maintenance activities usually cause brief, temporary increases in impacts, particularly on the road surface and associated ditches (USDA, 1999b).
Proper design, construction, and maintenance are fundamental to minimize these effects but cannot completely eliminate them.

1.3. Optimal extension and location of forest road network

The optimal extension of a forest road network is that which maximizes the value of the balance between the costs and benefits reported in the previous section. To consider all the factors involved is a challenging task that often needs to be simplified. One simplified (and often used) definition indicates that optimum road density and spacing is that which minimizes the total cost of timber transportation and road construction (Figure 2), (Bernetti, 1965; Tan, 1992).

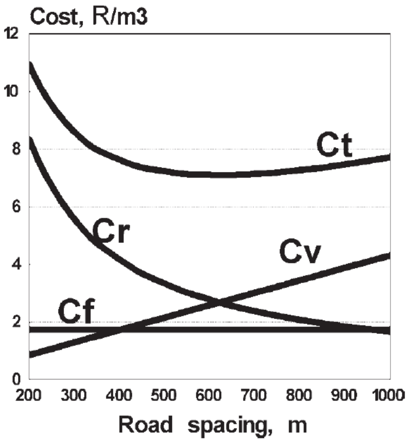


Figure 2 - Relationships between total cost (Ct), variable primary transport cost (Cv), fixed primary transport cost (Cf) and road cost (Cr) in harvesting and transport operations (FESA, 2005)

Optimal extension can be expressed using a road density index and spacing. An easily accessible surface (e.g. a forest) can be considered where the density and the spacing of forest roads provide a high efficiency for the execution of the operation, in relation to the characteristics (in particular slope and roughness) of the terrain.
It is important to have some indicators to evaluate the accessibility of a territory and therefore evaluate the possibility to easily access its resources. The three most used indexes that provide indication on the amount and distribution of roads in an area are road density (DV), spacing (S) and openness (SA).
The road density (DV) is expressed in meters per hectare (m/ha), summing the lengths of all the road sections inside an area and dividing the results by the area expressed in hectares.
Hippoliti (1976) indicated that an adequate road density is a DV value equal to the half of the mean slope value expressed in percentage.
Picman and Pentek (1998) found a road density of 14.7 m/ha as the optimum for a ground based skidding system using forest tractors in Croatia.
Cielo et al. (2003) for the Alpine region indicated an optimal DV value between 20 – 35 m/ha that can decrease to 10 -15 m/ha when the terrain condition allows easy movement off-road.
Spacing (S) represents the minimum distance between two roads, measured perpendicular to the contour-lines and expressed in meters (m) and can be calculated using the following formula:

$$S = \frac{10\,000}{DV}$$

From the spacing index, it is possible to derive an index representing the mean extraction distance (E):

$$S = \frac{S}{4} = \frac{2500}{DV}$$

This value represents an ideal situation in which the roads are parallel and the extraction direction is perpendicular at the roads. To have a realistic value, the result has to be multiplied by a coefficient that represents the real distribution of the roads. A coefficient value equal to 2 generally represents a normal forest road network (Dietz et al. 1984).
The effect of the roads on the surrounding forests is reduced proportionally with the increasing of the slope of the terrain (Hippoliti, 1976, Cielo et al. 2003, Klc, 2005).
The openness (SA) represents the ratio between the portion of the forest considered accessible and the total forested area, expressed in percentage. This index is the one that better represents the accessibility of an area. An area can be considered well accessible with values above the 70%, accessible with values between 60% and 70% and poorly accessible when the value is less than 60% (Dietz et al, 1984).
Hippoliti (1976) proposes methods to evaluate the accessibility of the territory based on the access time of an operator. An area can be considered easily accessible when it is reachable within a time of 30 minutes to go and return, and poorly accessible with a walking time within 60 minutes to go and return and not accessible past this value.
Determining appropriate road density and spacing is only the first step towards optimizing a forest road network. Optimal road density and spacing are therefore only indicators and do not take into consideration the restrictions dictated by the forest terrain and the spatial diversity of the forest stands. They do not give an indication on where roads should be located. The following step is then to determine the most efficient road layout.
Generally, the layout of a road network depends on the timber resources, terrain conditions, type of forest operations (afforestation, silvicultural treatment, fire protection, cutting system, logging and transport methods), technical equipment and machinery, labour techniques and costs, as well as other resource benefits to be considered (USDA, 1999).
A large branch of research on forest road networks regards the definition of the optimal road spacing and its location. Optimization of the road density can help minimize the total cost of harvesting (Ghaffariyan et al, 2010). Furthermore, forest road networks should be located as to minimize the total cost of both wood harvesting, wood transport and road construction and to also minimize adverse environmental impacts (Tan, 1999).
Two different approaches exist in determining the optimal value of road density and spacing, conventional forest road network planning and automated forest road locating (Tan,1992).
In conventional forest road network planning, the aspects involved with the presence of the roads (cost, benefit, terrain characteristic, environmental effects, and needs) are evaluated by experts on the basis of the available information. This represents a difficult process because some of these aspects are difficult to evaluate quantitatively.
Automated forest road locating can be divided in two primary step, network formulating and road locating.

Network formulating regards the determination of the nodes and links contained in the network and its formulation can be systematic (when it is based on some fixed rules) or empirical (when nodes and links are defined by a specialist).
In road locating, the most appropriate route connecting the nodes is found. For locating a road between a pair of points different mathematical optimization techniques have been applied. In this case, a series of grids representing the factors (Digital Terrain Model, extraction cost, penalty factors etc) that are included in the analysis have to be created.
Mixed integer mathematical programming and heuristic algorithms have widely been used to find the lowest cost solution for different type of fixed and variable cost problem related to road network location (Weintraub, 1986; Session, 1978; Anderson and Nelson, 2004; Najafi et al. 2008; Olsson and Lohmander, 2005).
Mattews (1942) first developed a model to define optimum road spacing based on minimizing the total cost of skidding and road construction.
Sessions and Chung, (2003) implemented an heuristic network algorithm in the NETWORK 2000 program to find the lowest cost solution in forest road location.
Chung et al. (2008) developed a model using a heuristic network algorithm to compare two timber transportation options (on-road transportation via new roads and off-road transportation using skidders).
Ghaffariyan et al (2010) used heuristic and linear programming to optimize the extension of the road network in a mountainous area of Austria.
Stuckelberger et al (2006) considered roading cost, ecological effects and suitability for cable yarding landings in their automatic road network planning in Switzerland.
Akay and Sessions (2005) implemented two optimization techniques (a linear programming for earthwork allocation and a heuristic approach for vertical alignment selection) in the model TRACER to design a route with the lowest total cost when considering construction, maintenance, and transportation costs, while conforming to design specifications, environmental requirements, and driver safety.

1.4. Design and construction of new roads

Designing forest roads in mountainous terrain involves various economic and environmental requirements. For this reason, road managers must consider as many alternative alignment alternatives as possible in order to find the solution that minimizes construction, maintenance cost and reduces environmental impacts.
The purpose of road design is to produce design specifications for road construction by determining the optimum road geometry that will accommodate the design vehicle configuration for load and alignment, and traffic volume, and provide for user safety, while minimizing the cost of construction, transportation, maintenance, and deactivation. The optimum road design should minimize impacts on other resources by minimizing clearing and road widths, minimizing excavation, using rolling grades, and installing proper drainage structures (B.C. Ministry of Forests, 2002).
Pozzati and Cerato (1984) argue that the only way to design the track of a forest road is through a survey on the terrain using an altimeter. However, in the last twenty years the tools for automatic road network design have considerably improved simultaneously with advancements in computing performance and the emerging availability of digital terrain data.
With the popularity of GIS in natural resource management, traditional road design techniques have been integrated into GIS. A computer program (PEGGER), was developed to automate initial forest

road design through the use of Geographic Information System (Rogers, 2001). By evaluating alternatives route in the office using GIS, a substantial amount of time can be saved and a better design may emerge (Rogers, 2005).
It is a complex task to include all of the factors involved in the construction of a forest road. The decision to construct a new road is normally taken by analyzing the costs and benefits estimated on the basis of available information such forest inventory documents, forest management planning documents, forest maps, aerial photos, topographic maps.
During the construction phase of a road project, the planning and design decisions that were made earlier are carried out on the ground to achieve the desired road standard in a way that is efficient and effective and results in minimal impact to the environment.
We will not focus the attention in this document on the further works and techniques to build a forest road. Although some research is on-going into the materials and methods for forest road building, the principles of road construction are now well-established and practical manuals are available (FESA, 2005; B.C. Ministry of Forests, 2002; Ryan T. et al. 2004).

1.5. Maintenance of the existing road network

Road maintenance is a vital activity to keep a road system serviceable and to ensure its drainage system is working properly. A well-maintained road can be protected from rapid deterioration, minimizing sediment production (Dubè et al. 2004) and reducing trucking costs (Brown, 2000).
Each year, a consistent amount of money is spent to upgrade and maintain forest road networks.
Oregon Department of Forestry (2000) describes the best management practices (BMPs) and the objectives to reach in setting up a forest road maintenance plan.
The 2 most important objectives are:

1. Maintain existing roads and structures to the intended design standards in order to ensure continued access to state-owned forest lands for the planned uses.
2. Minimize the adverse impacts to water quality, fish habitat, wildlife habitat and other natural resources that may be caused by the presence of the road system on state-owned forest land.

The basis for the development of a road maintenance plan is a thorough understanding of the road system, its characteristics and its needs. This is accomplished by establishing and maintaining an intensive inventory of the road system. The inventory has to provide the information necessary for identifying and prioritizing required maintenance. In addition, the inventory also provides the basis for the development of road improvement plans.
At a minimum, this inventory will categorize roads; identify drainage structures and rate their condition; identify and assess potential slope stability problems and maintain information related to the condition of the road surface.
The plan will identify the work to accomplish, the timing, the resources required to efficiently complete the work, and the methods for implementing the plan. Priorities will be assigned to each task, with the highest priority assigned to sites that have the highest potential for damage to the road or damage to down-slope natural resources.
Road maintenance activities can be divided into the following four basic categories: drainage, surface maintenance, cut and fill slopes and vegetation control (Oregon Department of Forestry, 2000).

Road surface: road surfaces should be graded only when necessary to maintain a smooth, stable running surface and to retain the original surface drainage. Excessive grading can result in increased rock wear and loss and can lead to unnecessary erosion.

Grading should cut deep enough into the surfacing material so that loosened material will mix, compact, and bind with underlying materials. If deep chuckholes or ruts cannot be graded out, the surface will be ripped and then graded and re-compacted to achieve proper binding. Otherwise, holes and ruts that are just filled or patched will quickly reform in the same locations. Oversized material that is brought to the surface during grading can be moved off to the side of the road.

At such a time, it will be necessary to add surfacing material in order to bring the road back into standard. This is due to the fact that over a prolonged period of use and maintenance, surfacing materials gradually break down or are lost to the side of the road. Steep road segments and curves experience the highest rate of rock loss. Eventually, the road will not match its designed standard.

Drainage Maintenance: culverts, catch basins, and ditches have to be cleaned as necessary to ensure proper drainage maintaining the flow capability required to remove surface runoff. Often, culvert cleaning is done in the summer months as part of routine maintenance. Culverts also need to be inspected and cleaned during high rainfall events to prevent plugging. Problems found during high rainfall events must be corrected immediately, because delay can result in serious road damage and costly repairs. During cleaning, floatable debris and accumulated sediment will be removed from the catch basin and placed where it cannot reenter the drainage system.

Frequent grading or "pulling" of ditches is usually unnecessary, and can actually cause excessive erosion, undermine cut slopes, and expose the toe of cut slopes to erosion. Remove other debris and vegetation only if obvious drainage problems are evident. Do not remove any more grass or vegetation than is necessary, as they prevent scouring and filter out sediment.

When "pulling" a ditch, avoid pulling the material across the road surface. This can lead to contamination of the surfacing material and increased erosion, especially during the first rains. Material pulled from the ditch can be windrowed on the inside road shoulder and hauled away for proper disposal.

Cut and fill slope: the key to maintaining cut and fill slopes, including side-cast materials, is to regularly observe them and note when and how changes to these features occur. Often, small slope failures can be symptoms of larger slope stability issues. Left untreated, these unstable features can fail suddenly and develop into debris flows and landslides that cause considerable down-slope damage. When changes to cut or fill slopes are noticed or suspected, consultation with geotechnical specialists can help ensure that the real problem is identified and the proper solution is formulated. Proper corrective measures can then be planned and implemented.

Vegetation control: over time various species of trees and shrubs will be established on the surface of the road prism. This vegetation may cause safety problems by reducing visibility. In some cases, the vegetation may also reduce the effectiveness of the drainage system or the stability of slopes. Where these conditions exist, some form of vegetation control may be needed.

Vegetation can be controlled manually, mechanically, or chemically. The method used will depend upon the characteristics of the vegetation, its location, and other factors.

When using chemicals, precautions will be used to avoid harm to non-target plants to prevent any of the pesticide from contaminating water.

Another important aspect regards the timing of the interventions. It is extremely important that any maintenance activity be conducted at a time when weather conditions allow for a minimal amount of soil disturbance and sediment movement. Some examples include, cleaning ditches during wet weather, causing excessive sedimentation; and grading a road during a hard rain event leading to the contamination of the surfacing material.

1.6. Forest road network planning and management

The meaning of planning is "to analyze the current situation in order to highlight gaps and needs and thus suggest possible interventions" (Hippoliti, 2003).
Have been already introduced that the correct planning and management strategies are fundamental in order to minimize the negative impacts due to presence of forest roads and at the same time satisfy the needs of accessibility of the territory.
Conventional forest road network planning regards the determination of road network density, road location and road quality with the objective of minimizing the total cost of terrain transportation, road transportation, road construction and maintenance. For example, forest planning and road management strategies should be integrated, due to the needs of accessibility established in accordance with the silvicultural operations plan. Moreover continual verification is required in order to find the best combination between functionality, technical aspects and environmental impacts.
But we have seen that nowadays the management of the existing forest road system considers other benefits (e.g. recreational value) and priorities (e.g. environmental aspects).
These changes in management strategies concerns have lead many timberland owners to conduct inventories of their forest road networks that are fundamental to better understand the condition of the road network and to set maintenance and upgrading priorities.
The priorities and the factors involved in forest road network management can vary substantially according to the area where the route is located and it is therefore fundamental to adapt the analysis to the specific situation analyzed.
According with Pozzati (1987) planning of forest roads is based on the detailed knowledge of the location of the forests, on its conditions, structure and silvicultural treatment, and of the presence and characteristic of the existing roads. The required information are normally contained in the Forest Management Plan of the area.
The examination of the accessibility of the forest should identify the part of the forest currently not accessible using the existing roads. These areas should be highlighted on the map, where will be integrated the development of the future state of the road network that meet the emerged needs. The need to preserve particular natural sites, or the estimate of high construction costs, due to the conditions of the terrain (excessive slopes, landslides, rock jumps, watersheds with steep and unstable banks, wetlands), has also to be evaluated.
The USDA in setting up its management strategies for the National Forest Transportation System pointed out the following six steps in the planning process aimed to producing needed information and maps (USDA, 1999):

<u>Step 1 – Setting up the analysis</u>: the analysis must be designed to produce an overview of the road system in its interdisciplinary scale. The output from this step will include a list of information needs, and a plan for the analysis.
<u>Step 2 – Describing the situation</u>: will be describing the existing road system in relation to the current forest plan direction. Products from this step include a map of the existing road system, descriptions of

access needs, and information about physical, biological, social, cultural, economic, and political conditions associated with the road system.

Step 3 – Identifying issue: will be identifying important road-related issues and the information needed to address these concerns. The output from this step includes a summary of key road-related issues, a list of screening questions to evaluate them, a description of the status of relevant available data, and what additional data will be needed to conduct the analysis.

Step 4 – Assessing benefit, problem and risks: after identifying the important issues, the major uses and effects of the road system will be examined including the environmental, social, and economic effects of the existing road system, and the values and sensitivities associated with areas in which roads are not present. The output from this step is a synthesis of the benefits, problems, and risks of the current road system and the risks and benefits of building roads into areas without roads.

Step 5 – Describing opportunities and setting priorities: will be identified management opportunities, established priorities, and formulated technical recommendations that respond to the issues and effects. The output from this step includes a map and descriptive ranking of management options and technical recommendations.

Step 6 – Reporting: will be producing reports and maps that portray management opportunities and supporting information important for making decisions about the future characteristics of the road system. This information sets the context for developing proposed actions to improve the road system and for future amendments and revisions of forest plans.

1.7. GIS tools in forest road network management

Marble et al. (1984) define GIS as "a set of tools for the input, storage and retrieve, manipulation and analysis, and output of spatial data."

The functionality of a GIS can be subdivided into four main components or subsystems: data input, data storage and management, data manipulation and analysis, data output (Malczewski, 1999).

Input data used into GIS software can derive from 4 type of acquisition: digitizing, scanning, remote sensing and Global Position System (Malczewsky, 1999).

Geographic Information Software allows one to analyze and link together through algorithms various spatial information.

In a GIS software all geographic information is represented and managed through two structures, vector data and raster datasets.

Vector data can be points, lines or polygons. Point features can be used for example to represent a deposit emplacement, a limiting point, a landslide point along a road. Lines features are often use to represent networks (pathways, lines of communication, the ordinary roads or forest roads). Finally the polygons can be used to represent well-defined areas such as administrative boundaries. To the vector file (features) is then associated a table that contains all the information about each item (objects) associated with the vector file to describe its characteristic.

A raster data structure is based on a (usually rectangular, square-based) tessellation of the 2D plane into cells. To each cell is assigned a value (for example, the average elevation) and the information of its spatial location.

A raster is normally used to represent continuous spatial data (digital terrain models, map of the slope) or defined information when is derived from the conversion of a vector file.

A good way to manage the information relatives to forest road networks can be based on storage of the information within a geo-database. A geo-database is an object-oriented data model that optimizes the

management of geographic data and simplifies the writing of any applications for the management, integration and processing of the geographical data (ESRI, 2011).
In a geo-database can be stored both raster and vector data; in particular a geodatabase can manage information in the form of rules and topological relationships. In the particular case of forest roads, using a geo-database is possible to manage the set of geographic data (e.g. roads, emplacement, interconnections with public roads) as a single network.
A geo-database also can be continually updated and improved with the addition of new information representing an open and versatile tool, particularly suitable for the management of forest roads and or more widely than forests and pastures.
Where possible, modern technology such as Global Positioning Systems, Geographic Information Systems, data recorders and data base software are used to collect and manage the information. GIS especially plays a key role in supporting the analysis process and have been largely used in evaluation and management of forest road networks (Floris et al. 1999; Cielo et al. 2003; Klc, 2005; Gumus et al. 2007; Nevecerel et al, 2007; Cavalli and Grigolato, 2010).

1.8. Spatial Multi-Criteria Decision Analysis Process

The decision support field is the "development of approaches for applying information systems technology to increase the effectiveness of decision makers in situations where the computer can support and enhance human judgment in the performance of tasks that have elements which cannot be specified in advance" (Sol, 1983).
Any decision-making process begins with recognizing the decision problems. A spatial decision problem is the difference between the desired and the existing state of a real-world geographical system.
In this context, a decision is needed when a problem or an opportunity exists -- when something is not as it should be or when something can be improved. Simon (1960) suggests that any decision-making process can be structured in three major phases (3): *intelligence* (is there a problem or an opportunity for change?), *design* (what are the alternatives?), *choice* (which alternative is best?).

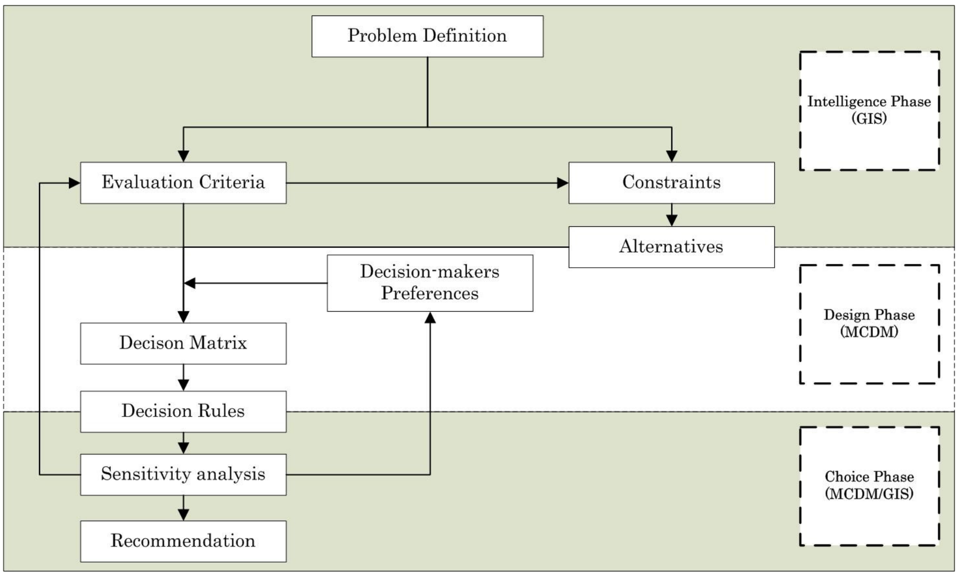


Figure 3 - Framework of spatial multi-criteria decision analysis

The major part of the decision-making process (also called "*intelligence*") regards the scanning of the decision environment to identify the elements calling for decisions and the collection of all the needed data in order to represent the real world in the GIS database. In this phase, GIS is a fundamental tool in coordinating situation analysis through its capability to integrate data and information from a wide range of sources and generate the different evaluation criteria and constraints that represents the input to the spatial multi-criteria decision analysis.
The following *design* phase regards the generation of alternative decisions. Alternatives may involve actions such as "construct a new road" or "decommission an existing road" or "allocate resources for road system maintenance".
Typically, spatial decision alternatives are derived by manipulation and analysis of the data and information stored in the GIS and should take into consideration the complexity of the relationship of some spatial decision problems that are particularly difficult to represent.
In this phase, Multi-Criteria Decision Methods (MCDM) provide the tools for aggregating the geographical data and the decision-makers preferences into a uni-dimensional value or utility of alternative decisions. The preferences are typically expressed in terms of the weights of relative importance assigned to the evaluation criteria under consideration. After the determination of the set of alternatives, attributes and associates weights, the input data can be organized in the form of a decision matrix.
In the *choice* phase, each alternative is evaluated and analyzed in relation to others in terms of a specified decision rule or function that is used to aggregate the evaluation criteria and to rank the alternatives under consideration.
Subsequent to obtaining a ranking of alternatives, sensitivity analysis should be performed to determine robustness (effects of the changes in the inputs on the outputs). The end results are represented from a set of recommendations for future action.

1.8.1. Criteria Evaluation

The set of criterion maps and their hierarchical structure is a representation of a particular decision situation or a particular segment of the real world geographical system. For any given objective, several different attributes might be necessary to provide a complete assessment of the degree to which its objective might be achieved. Once an objective has been identified, the evaluation criteria (attributes or objective) that are involved in its achievement should be identified.
The set of evaluation criteria and their hierarchical structure is obviously problem specific.
A set of attributes is considered complete when it covers all relevant aspects of a decision problem and adequately indicates the degree to which the overall objective is achieved.
The set of evaluation criteria for a particular decision problem may be developed through an examination of the relevant literature (Winpenny, 1991), analytical study (MacCrimmon, 1969) and opinion (Keeney and Raiffa, 1976).
Once the hierarchical structure of objectives and attributes is established, each criterion should be represented as a map layer in the GIS database.
This operation involves all the analysis capabilities of GIS software. Relevant data is acquired and stored in a GIS database, and then the data is manipulated and analyzed to obtain the information regarding a particular criterion.
A criterion map represents the spatial distribution of an attribute that measures the degree to which its associated objective is achieved (e.g. cost criterion map, proximity criterion map). Given the variety of scale on which a criterion can be measured, multi-criteria decision analysis requires that the values

contained in the various criterion map layers be transformable to comparable units. This is because if we want to combine the various criterion map layers, the scales must be commensurate. Different approaches can be used to make criterion maps layers comparable including deterministic, probabilistic and fuzzy methods.
Linear scale transformation is the most frequently used deterministic method for transforming input data into commensurate criterion maps. The linear scale transformation methods convert the raw data into standardized criterion scores (Voogd, 1983; Massam, 1988).
The two most often used procedures are the *maximum score* (1) and the *score range* (2) procedures.

$$X'_{ij} = \frac{X_{ij}}{X_{max}} \qquad (1)$$

$$X'_{ij} = 1 - \frac{X_{ij}}{X_{max}} \qquad (2)$$

Where x'_{ij} is the standardized score for the *i*th object (alternative) and the *j*th attribute and x_{ij} is the raw score and x_{max} is the maximum score for the *j*th attribute. The value of standardized scores can range from 0 to 1.

1.8.2. Decision alternatives and constraints

Decision options are the alternative courses of action among which the decision-maker must choose. Each spatial decision alternative consists of at least two basic elements: action (what to do?) and location (where to do it?). Alternatives can be represented by the possibility to construct a road or not, or the best location where to construct the road.
Constraints are limitations imposed by nature or by human beings that do not permit certain action to be taken (Keeney, 1980). A constraint can for example be represented by the available economic resources to complete a specified project (*budget constraints*). In practice constraints are limitation on the set of decision alternatives.

1.8.3. Criterion weighting and Multi-Attribute decision rules

The purpose of the criterion weighting is to express the importance of each criterion relative to other criteria, the larger the weight, the more important the criterion is in the overall utility. The derivation of the relative weights is a fundamental step in the decision-maker's preferences definition.
Many different criterion-weighting procedures exist. The most popular are ranking, rating, pairwise comparison (Saaty, 1980) and trade-off analysis (Lai and Hopkins, 1989).
Once assigned, the weights of each criterion these has to be combined using a multi-criteria decision rule.
A decision rule is a procedure that allows for ordering alternatives (Starr and Zeleny, 1977; Chankong and Haimes, 1983).
Additive decision rules are the best known and most widely used Multi-Attribute decision rules in GIS-based decision making. The most commonly used methods are the *simple weighting methods*, the *value/utility function approaches* and the *Analytic Hierarchy Process* (Saaty, 1980).

1.8.4. Spatial Decision Support System

In literature, there are several different definitions of Spatial Decision Support System (SDSS). Gorry and Morton (1971) define SDSS as an "interactive computer based systems that decision makers utilize data and models to solve unstructured problems", while Sprague and Watson, (1986) define SDSS as "Any system that makes some contribution to decision making". Malczevski (1999) states that SDSS is an interactive, computer-based system designed to support a user or group of users in achieving a higher effectiveness of decision making while solving a semi-structured spatial decision problem.
A spatial decision support system typically consists of the combination of a decision support system (DSS) and a Geographic Information System (GIS).
Densham (1991) suggests four distinguishing capabilities and functions of an SDSS. The system should:

- Provide mechanisms for the input of spatial data
- Allow representation of the spatial relations and structures
- Include the analytical techniques of spatial analysis
- Provide output in a variety of spatial forms, including maps

The structure of SDSSs can be described by identifying the mayor components of the system. An SDSS typically contains three generic components and relative functions (Table 1):

Table 1 – SDSS Components and Functions

Components	Function	Types
Database and management: contains the functions to manage the geographic data base	Types of data	Locational (e.g. coordinates), Topological (e.g. points, lines, polygons and relationship between them), Attributes (e.g. geology, elevation, transportation network)
	Logical data view	Relational DBMS, Hierarchical DBMS, Network DBMS, Object-oriented DBMS
	Management of internal and external databases	Acquisition, Storage, Retrieval, Manipulation, Directory, Queries, Integration
Model base and management: contains the library of potential models that can be used to forecast the possible outcomes of decisions	Analysis	Goal seeking, Optimization, Simulation, What-if
	Statistic and forecasting	Exploratory spatial data analysis, Confirmatory spatial data analysis, Time series, Geostatistics
	Modeling decision's maker preference	Value structure, Hierarchical structure of goals, evaluation criteria, objectives and attributes, Pairwise comparison, Multi-attribute value/utility
	Model uncertainty	Data uncertainty, Decision rule uncertainty, Sensitivity analysis, Error propagation analysis
Dialog Generation and Management System: which manages the interface between the user and the rest of the system	User friendliness	Consistent, natural language comments, Help and error messages, Novice and expert mode
	Variety of dialogue style	Command lines, Pull-down menus, Dialogue boxes, Graphical user interfaces
	Graphical and tabular display	Visualization in the decision space, Visualization in the decision outcome space

1.8.5. Multi-Criteria Spatial Decision Support System

A Multi-Criteria Spatial Decision Support System (MC-SDSS) integrates the GIS-based data processing and analysis with the multi-criteria decision analysis process. The way the two components are integrated depends on the philosophy behind the design strategy (e.g. a system for supporting a single-user versus a group decision making), the types of decision problems (e.g. environmental versus urban/transportation planning decision problems) and the MCDM models incorporated into the MC-SDSS system. Despite these differences, the basic structure is composed of three main elements: a Geographical Data Management and Analysis Toolbox, a multi-criteria model Toolbox and a user interface (
Figure 4).

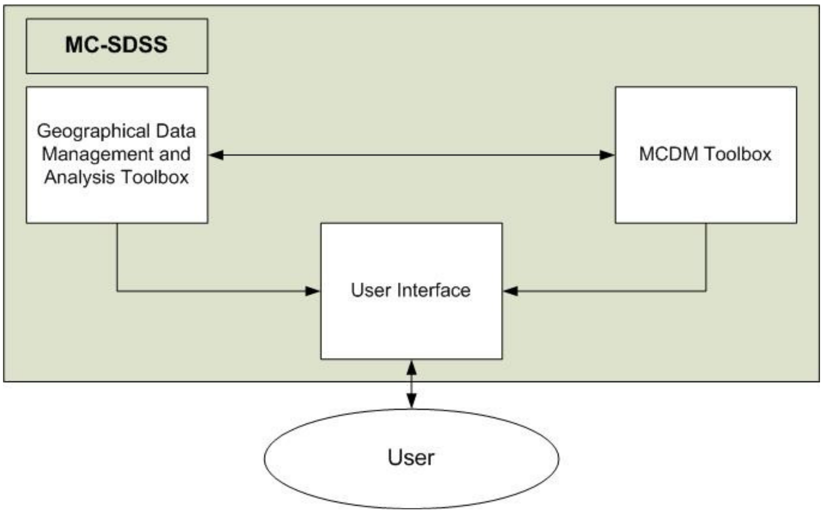


Figure 4 - Framework for MC-SDSS: toolbox approach

The fundamental issue in designing the MC-SDSS data module is the compatibility of the data construct between the GIS/DBMS model and the MCDM modeling system (Nyerges, 1993). The raster-based GIS and relational DBMS are more appropriate for multi-attribute decision modeling. In this case, a grid-based spatial construct provides a convenient data model for reprinting attribute data in tabular format (decision matrix) which can serve as data input multi-attribute modeling. To this end, a cell of a raster layer (or a combination of cell) can be considered as a decision alternative, and each data layer represent a single attribute (evaluation criterion) (Eastman et al. 1993; Pereira and Duckstein, 1993; Malczevski, 1996).Thus there is a direct parallel relationship between the GIS data model and the data input for multi-attribute decision analysis.
The ultimate objective of a computer based spatial decision support system or multi-criteria spatial decision support system for integrated ecosystem management is, or should be, to improve planning and decision making processes by providing useful and scientifically sound information to the actors involved in these processes, including public officials, planners and scientists, and the general public.

1.9. Multi-Criteria Spatial Decision Support System in forest road management

The correct approach to the evaluation of a forest road network, the evaluation of the related problem and the definition of the management priorities and opportunities should be based on a multifunctional approach (Gumus et al. 2007) that considers the economic, social and environmental aspects involved.
The development of decision support tools is based on the development of models. According to Dykstra (1984) a model is a representation or abstraction of a real object or a real situation.
Among these models is the Multi-Criteria Decision Making (MCDM) or multi-criteria decision models (Triantaphyllou, 2000).
In a Multi-Criteria Evaluation (MCE), an attempt is made to combine a set of criteria to achieve a single composite basis for a decision according to a specific objective (Eastman *et al.* 1993).
One advantage of MCE is that it provides a flexible way of dealing with qualitative multidimensional environmental effects of decisions (Munda et al. 1995).
Although a variety of techniques exist for the development of weights for the criteria, one of the most promising would appear to be that of pairwise comparisons developed by Saaty (1980) in the context of a decision making process known as the Analytical Hierarchy Process (AHP). In the pairwise comparison method, the decision-maker is asked to give the relative importance to the criteria by comparing them two by two.
Integrating GIS-based data processing and analysis techniques and Multi-Criteria Decision analysis we move into the concept of Multi-Criteria Spatial Decision Support System (MC-SDSS) (Malczewski, 1999).
The choice of a MC-SDSS using AHP in the evaluation of interventions relating to the maintenance of forest roads has been proposed and motivated in part by Coulter et al. (2006).
Cavalli et al (2011) show that AHP can be an appropriate method to define where the construction of a road is technically possible and meanwhile it gives a considerable benefit to the management of a productive forest area.
Mohammadi Samani (2010) used AHP and GIS software for forest road network planning in Caspian Forest considering 8 kinds of maps as criteria.
Abdi et al. (2010) developed a model to evaluate forest road networks with regard to technical requirements and costs using GIS and AHP.
Shiba (1995) used AHP to identify the benefit structure of a road network and showed that AHP is particularly useful tool for resolving political, economic and environmental conflicts.

1.10. Aims of the work

The work is divided in 3 sections (Figure 5).
The first section "*Creation of the cadastre of the primary forest road network for Veneto Region*" describes the process and the methodologies adopted to create a forest road network cadastre.
The aims of this section are:

- to create of a geo-database containing the basic information about the forest road network and its functional classification at a regional level;
- to develop and apply in some sample areas a protocol of inventory to complete and update the operative forest roads geo-database;
- to develop of a density index to evaluate the endowment of forest roads at a local level.

In the second section "*GIS-based models to support decisions in forest road network planning and management*" are developed three tools that use the information contained in the operative forest road network geo-database to elaborate thematic map useful for forest road network planning and management.

The aims of this section are:

- to develop a DSS-Tool (FORACCESS) to evaluate the accessibility of the territory and the needs of construction of new roads;
- to develop a DSS-Tool (FORSE) to evaluate the suitable wood extraction system;
- to develop a DSS-Tool (ROADGRAD) to evaluate the forest road gradient.

The third section "*Spatial Multi-Criteria Decision Process to define maintenance priorities and management opportunities of primary forest road network*" will focus the attention on a methodology to define the optimal maintenance strategy of a forest road network using Analytic Hierarchy Process.

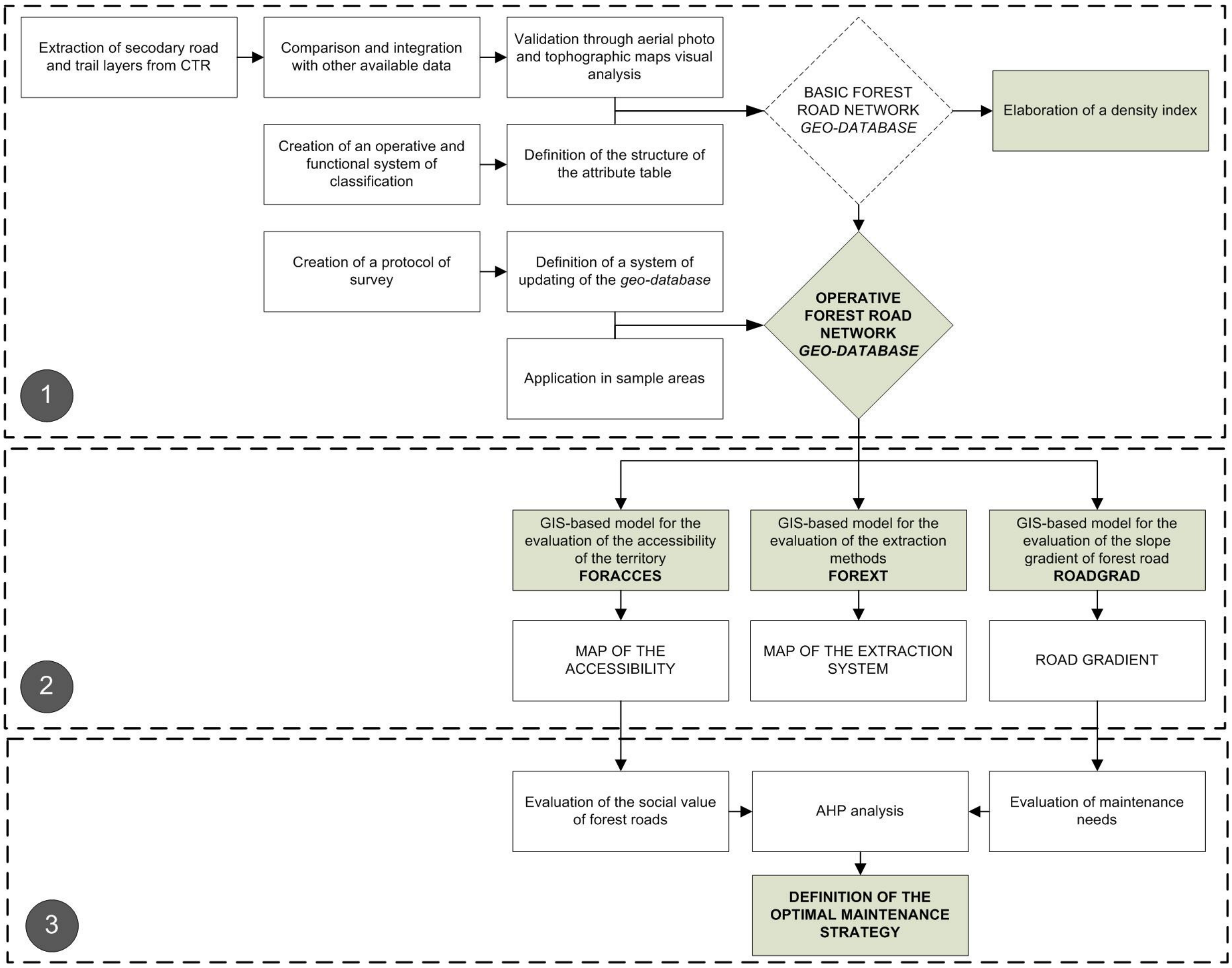


Figure 5 - Layout of the work

Chapter 2: Inventory of the primary forest road network for Veneto Region

2.1. Introduction

Knowledge about the extension and the characteristics of the forest road network is fundamental in order to support planning and address the control and the management of the territory.
For this reason, the availability of a geographic-database where all the section of forest roads and the related information are included is considered to be essential to ensure that the forest road network meets current and future land and resource management objectives.
The lack of this informative level in Veneto Region, where limited information about the presence of forest roads were held only with local authorities (Comunità Montane) represented the driving force for the execution of the present work.
The creation of a new inventory, with an operative function, which can be used to support forestry and agricultural activities can bring many positive effects in the organization and management of the regional forestry and pastoral resources.
To achieve this objective the latest technology will be used both to gather information by GPS instruments and to manage and data-processing using spatial information management software (GIS).
The creation of the inventory of the primary forest road network for Veneto Region is the first part of the wider project "Creating of support tools for forest road system planning at a regional level" founded by the Veneto Region.

2.1.1. Mountainous region and forest road network management

According to art. 23 of the regional act LR 52/1978 of the Regione del Veneto to achieve an economic and efficient management of forests and pastures and to encourage their expansion and improvement, an adequate service road network may be established so long as it meets the environmental protection and soil conservation.
The existing road system in many Alpine regions was largely constructed over the last 50 years mainly to guarantee access to areas for timber harvesting and to develop other practices such as sheep-farming.
In the last two decades the type of use of the resources and the interests driving natural resources management has substantially shifted toward a mixture of priorities such as recreational activities, watershed control, wildlife improvement and silvicultural needs.
Under this changing perspective, even the management of the existing forest road system needs to evolve toward a paradigm where other benefits and priorities must be considered and methods must be developed. In particular, all the possible impacts that the road infrastructure can cause to a vulnerable environment as the mountainous one and the different positive effects that the presence of a road can arise to the management of the territory must be considered.
These changing management strategies concerns need to be supported from a deep knowledge of the existing forest road network and have led many timberland owners to conduct inventories of their forest road networks.

In fact, the basis for the development of a road management plan is a thorough understanding of the road system, of its characteristics and its needs, and this is accomplished by establishing and maintaining an intensive inventory of the road system (Oregon Department of Forestry, 2000).
In addition, forest road network management in the mountainous area of Veneto faces many structural problems that make particularly difficult the achievement of the goal to maintain its efficiency.
The most evident problem is represented from the quality of the information about the presence and the characteristic of the forest roads. The informative level is actually poor and incomplete. Moreover data is often present in different formats making it impossible to have an organic picture of the forest road system.
The compulsory endowment of a forest road network cadastre for the Province and the Comunità Montane indicated in art. 6 of the the regional act LR 14/1992 of the Regione del Veneto did not represent at this time a sufficient tool to achieve a good level of knowledge.
This lack of an organic picture about the extension and the condition of the forest road network at the Regional level makes increasingly difficult the planning of founding and sharing in order to guarantee the correct execution of the maintenance and upgrade operations or the allocation of the financial resources for new road construction. Moreover, the economic resources are often limited and needed to be oriented in the optimal way in order to meet the objective related to the management of the territory.
The availability of a geographic database, which contains all the sections of roads within the mountainous forest and pastoral area of the Veneto, is thus considered an essential tool to support the planning of the interventions for the maintenance and management of the mountain territory.
The arrangement of unique and standardized information will firstly allow estimations of the total extension and the quality of the endorsement of forest roads of the territory.
Knowledge of the existing forest road network and its condition in relation to the characteristics and importance of the relative openness gives the base for planning of new roads construction and for the maintenance of the existing.
A comprehensive inventory has to provide the information necessary for identifying and prioritizing required maintenance intervention and in addition, provide the basis for the development of road improvement plans. As a minimum, this inventory will categorize roads, identify drainage structures and rate their condition, identify and assess potential slope stability problems, and maintain information related to the condition of the road surface (Oregon Department of Forestry, 2000). The possibility to easily store and handle spatial data, to locate features on the terrain and to perform spatial analysis make GIS the ideal tool to manage information about forest road network.
Examples of methodology for the creation of forest road network cadastre is given by Pentek et al. (2007), Pentek (2008) for the primary and secondary forest traffic infrastructure cadastre of Croatia, Cielo and Gottero (2004) for the Piemonte (Italy), USDA Forest Service (1999c) for the national forest road system of United States, Brassel and Lische (2001) for the forest road system of Switzerland, Gumus (2009) for the Turkish forestry.

2.2. Aims of the work

- To create the *Basic Forest Road Network Geo-database,* a first informative layer to gain a general knowledge about the presence of forest roads within Veneto;
- to elaborate a series of density indexes to indicate the presence of forest road at a municipal level;
- to create a survey protocol to update the information contained in the basic forest road network geo-database turning it into an operative tool.
- to apply the survey protocol and thus create the O*perative Forest Road Network Geo-database* in some sample areas.

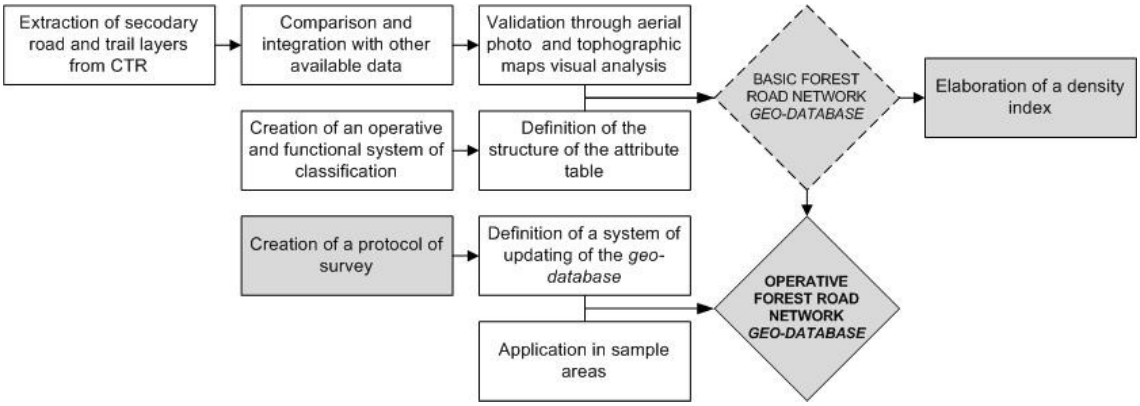


Figure 6 – Layout of the study

2.3. Material and methods

2.3.1. Study area

Veneto is the 8th largest region in Italy, with a total area of 1 839 122 ha, it is located in the North-Eastern part of Italy and is bordered to the East by Friuli Venezia Giulia, to the South by Emilia-Romagna, to the West by Lombardia and to the North by Trentino-Alto Adige and Austria.

The territory is divided into 7 provinces and 581 municipalities.

The mountainous area extension as considered in the present work is 6 198 km^2 (Figure 7). It is included in 5 province and 119 municipalities and its divided in 19 administrative units called Comunità Montana.

The extension of the surface indicated as forest is equal to 397 899 ha (INFC, 2005) of which 91 390 ha are classified as productive forests. The two most represented species used for productive purpose are the Norway Spruce (*Picea abies*) and the European beech (*Fagus sylvatica*).

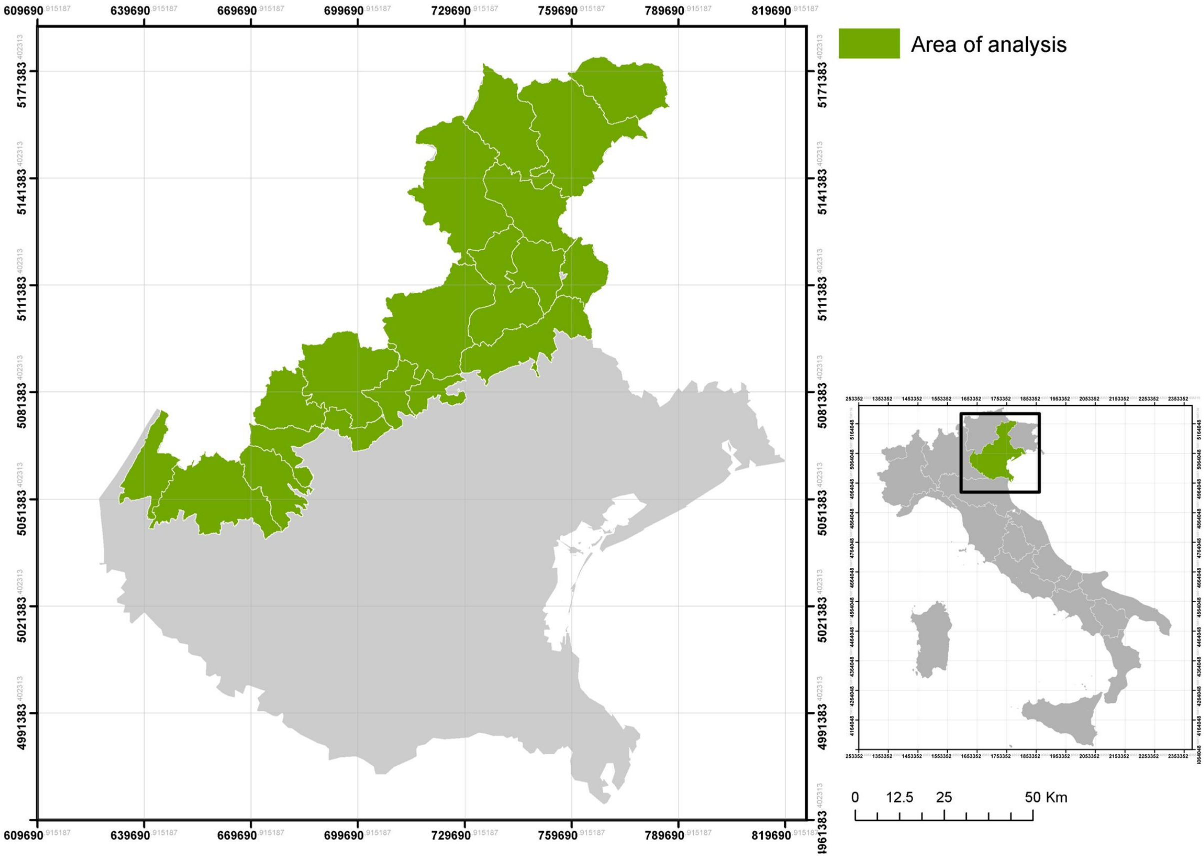


Figure 7 – Location of the study area

2.3.2. Data capture and organization of the information

The process to create the basic informative layer of forest road network started with the acquisition of all the available geographic information useful to get a cognitive frame-work of the forest road within the area of interest. Data with different origin and level of detail have been analyzed and integrated. Acquired geographic information regards:

- available forest road network information for each Comunità Montana and Regional Forest Service
- Technical Regional Map (1:5 000 – 1:10 000)
- Regional Forest Type Map
- Soil Usage Map
- Forest Management Plan Map
- aerial photos colored (2003, 2007, 2009) black and white (1957) and false color (2007)
- administrative boundaries of Municipalities, Provinces, and Comunità Montane
- Topographic Maps (1:10 000 – 1:25 000)
- Digital Elevation Model of the terrain at a resolution of 25m and 10m

The available information regarding the forest road network highlighted that at a regional level it is completely missing any information uniformity. In particular, the *geo-databases* owned by the Comunità Montane were in different formats (.shp, .dxf, .dwg) and in some cases the data was available only in a paper or .pdf format. Furthermore, information about the characteristic of the forest roads was in most of the cases missing.
The baseline was then to create a first level of information where all the tracks of the roads considered of interest for the management of the mountainous territories were represented.
The process of examination and standardization of the data was structured in different levels, from the extraction of the raw data from the regional technical maps to the comparison, control and integration with all the available information (Figure 8).

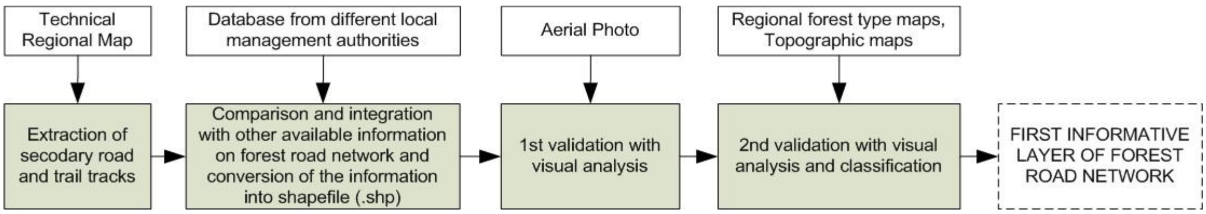


Figure 8 – Process of creation of the first informative layer of forest road network

Once completed, the resulting layer was split into the different territorial management units (Comunità Montane). The division into territorial units provides more flexibility in file management and updating.
The layer was created in two different reference systems, the national system Gauss-Boaga Rome 40 (West Zone), and the UTM, 32N.
The result led to the production of an informative level (Basic Forest Road Network Geo-database) based on the presence and the extension of the forest roads at the regional level.
The layer was prepared in vector shapefile polylines with associated all the descriptive fields (attribute table) contained the characteristics and the information useful for the management of each road.
When information was present in the local forest road network database or in the topographic maps and when attributes were certainly identified from the aerial photo, these were included in the attribute table during the visual validation in the office. In all the other cases the attribute tables will report the value NC (Not Classified). The following table (Table 2) reports the structure of the attribute table of the forest roads *geo-database*.

Table 2 - Structure of the attribute table of the forest roads geo-database

Field Name	Field Element	Description	Format
Local Authorities	Text	Indicates the Local Management Authorities for the road	Text (80 characters)
Municipalities	Text	Indicates the Municipality in which the road is located	Text (25 characters)
Toponym	Text	Indicates the closest toponym to the centroid of the road	Text (50 characters)
Restriction	YES/NO	Presence of bar or padlock at the beginning of the road	Text (3 characters)
Type of access	P RA RS NC	Public Restricted access indicated with road sign Restricted access indicated with road sign and bar Not Classified	Text (2 characters)

Field Name	Field Element	Description	Format
Functional Classification	O C MF FOR NC	Ordinary roads Access roads Multi-function roads Forest roads Not classified	Text (3 characters)
Operative Classification (Trafficability)	1 2 3 4 0 NC	Low mobility and high load capacity Low mobility and medium (+) load capacity High mobility and medium (-) load capacity High mobility and low or null load capacity Not practicable with vehicles Not classified	Text (2 characters)
Surface type	AS C M N A NC	Tarred road Paved with cement Gravel road Natural Other type of surface Not classified	Text (2 characters)
Surface condition	R PD D NC	Regular Partially damaged Damaged Not classified	Text (2 characters)
Width	Value in meters	0 if not surveyed	Numeric
Gradient	Value in %	0 if not surveyed	Numeric
Drainage structure	YES/NO	Presence of drainage structure	Text (3 characters)
Drainage structure functionality	YES/NO	Functionality of the drainage structure	Text (3 characters)
Retaining walls	YES/NO	Presence of retaining walls	Text (3 characters)
Retaining walls condition	GOOD/POOR	Condition of the retaining walls	Text (4 characters)
Data collector	Name	Name of the people / structure that made the survey	Text (20 characters)
Date	gg/mm/yyyy	Date of the survey	Text (15 characters)
Shape length	Value in meters	Length of the track	Numeric

2.3.3. Definition of a functional and operative classification of forest roads

Current regional legislation (LR n° 14/92) defines "forest roads" as the roads that are "situated inside forest and pasture land" (art. 2). According to the law, the ordinary roads (public transit) and the roads that provide access to human settlement are excluded, even if in many case this roads have a considerable importance in support forestry and agricultural activity.

As suggested from Hippoliti (1976), Floris et al (1999) and Calvani et al. (2003) the term forest roads have to include both "exclusive forest roads" (the part defined from the law) both "road of forestry interest" when there is a multi-functionality that includes the access and the support to forestry activity.

To better evaluate the extent and the level of service of the road network Cielo et al. (2003) included in a regional database also the roads that provide access to agricultural areas.
The requirement to classify the road network is determined by the need to codify the trafficability and the operative level and thus improve safety on these roads.
Nowadays the most considered classification system (Table 3) is still the one proposed from Hippoliti (1976) that reports a generic subdivision of the roads according with the function (primary or secondary) and in terms of practicability (transit for trucks or transit for tractor).

Table 3 - Classification system proposed from Hippoliti (1976)

Primary road	W. Min.	W. Prev	M.S. Opt	M.S. max	S max	R min
	m	m	%	%	%	m
Primary for Truck	3.5	5-6	3-8	10	14	10
Secondary for Truck	3	4-5	3-8	12	18	7
Tractor road	2.5	3-4	3-8	14	25	5
Secondary road						
Primary skid road	2	3	5-10	20	30	-
Secondary skid road	2	3	-	-	40	-

Notes: W. Min: minimum carriageway width (m); W. Prev: prevalent carriageway width (m); M.S. Opt: optimal mean gradient (%); M.S. Max: maximum mean gradient (%); S max: maximum gradient (%); R min: minimum radius of curvature (m)

This classification can be accepted for the purpose of a general overview of an area but can present some limitations if applied at an operational scale, particularly in terms of support for detailed planning of forest operation or forest fire defense operation. Moving to an operative level requires a higher detail in the classification, as proposed for example from Calvani et al. (2003) for forest fire fighting.
During the creation of the structure of the Regional geo-database for forest roads, two systems of classification have been elaborated, a functional classification (Table 4) and a practicability classification (Table 5) structured to support operative decisions.

Table 4 - Proposed road classification according to its function

Class	Function	Description
O	Ordinary roads	National and regional major roads generally not used for forest purposes
C	Access roads	Road manly used to access of connect human settlement or productive activity. If outside urban areas rarely used for forest purposes.
MF	Multi-function roads	Secondary roads with free access commonly used for rural, forestry or recreational purposes
FOR	Forest roads	Forest roads with restricted access used only for forestry purposes (as defined from L.R. n°14/92)
NC	Not classified	Network of not permanent skid roads or trail not practicable with vehicles, including also recreational trails

Table 5 - Proposed road classification according to the operative level

Class	Description	Forest operations
1	Low mobility and high load capacity	Truck with trailer
2	Low mobility and medium (+) load capacity	Truck
3	High mobility and medium (-) load capacity	Forwarder or tractor with forest trailer
4	High mobility and low or null load capacity	Small tractor with single axe carriage
0	Not permanent skid roads or trail not practicable with vehicles	

The requirement to develop the classification systems of the road network is determined by the need to codify the trafficability and the operative level and thus improve safety on these roads.
The function of each road has been defined during the visual evaluation. For what concerns the operative level, the assigned values have to be considered only as an indication that needs to be validated in the field. For that reason, in many cases this value has been voluntary under-estimated.

2.3.4. Evaluation of the forest road density

The topological aspects of forest roads are most commonly quantified only by length and road density, which are often poor indicators of many aspects of the network relevant to forest managers.
The road density (DV) is expressed in meters per hectare (m/ha), summing the lengths of all the road sections inside an area and dividing the results by the area expressed in hectare.
An evaluation of the Road Density Index for each administrative unit (Municipality and Comunità Montana) has been done through the analysis of the information about forest road network extension contained in the *Basic Geo-database*.
Road Density (DV) was calculated extracting the section of roads classified with an operational level of 1, 2, 3 and 4 and a functional class C, MF and FOR.
As such, only that parts of roads that are practicable using vehicles and are useful for forest and territory management have been considered.
Using this data, 8 types of Road Density value have been calculated to correctly evaluate the variability of situations present into the territory of Veneto Region:

- INDEX A: represent the density of road with an operational level of 1, 2, 3, and 4 within the forested area (as indicated in the Forest Type Regional Map) applying a buffer of 50 m.
- INDEX B: represent the density of road with an operational level of 1, 2, and 3 within the forested area (as indicated in the Forest Type Regional Map) applying a buffer of 50 m.
- INDEX C: represent the density of road with an operational level of 1, 2, 3, and 4 within the forested area (as indicated in the Forest Type Regional Map).
- INDEX D: represent the density of road with an operational level of 1, 2 and 3 within the forested area (as indicated in the Forest Type Regional Map).
- INDEX E: represent the density of road with an operational level of 1, 2, 3, and 4 within the managed area (as indicated in the Forest Management Plan).
- INDEX F: represent the density of road with an operational level of 1, 2 and 3 within the managed area (as indicated in the Forest Management Plan).
- INDEX G: represent the density of road with an operational level of 1, 2, 3, and 4 within the productive forested area (as indicated in the Forest Management Plan) applying a buffer of 50 m.

- INDEX H: represent the density of road with an operational level of 1, 2, 3 within the productive forested area (as indicated in the Forest Management Plan) applying a buffer of 50 m.

After the determination of DV values, through a descriptive statistical analysis, the mean, the standard deviation were extracted and the first and third quartiles among all the DV values calculated for each Municipality and for each Comunità Montana.
Based on these statistical values, a set of normalized indices were then defined, in order to make comparable the different road density values at a Regional level (Table 6).

Table 6 - Criteria for the normalization of the indexes of road density

Index value	Condition	Meaning
1.00	DV < first quartile	Low road density
0.75	arithmetic mean < DV > first quartile	Medium-Low road density
0.50	third quartile < DV > arithmetic mean	Medium-High road density
0.25	DV > third quartile	High road density

The analysis led to the creation of a shapefile reporting the results of the different values of road density for each municipality within the mountainous area of Veneto Region.
The resulting map layer additionally contains a series of descriptive fields to support the evaluation and the interpretation of the calculated road density indexes. Information for each municipality included in the attributes table is:

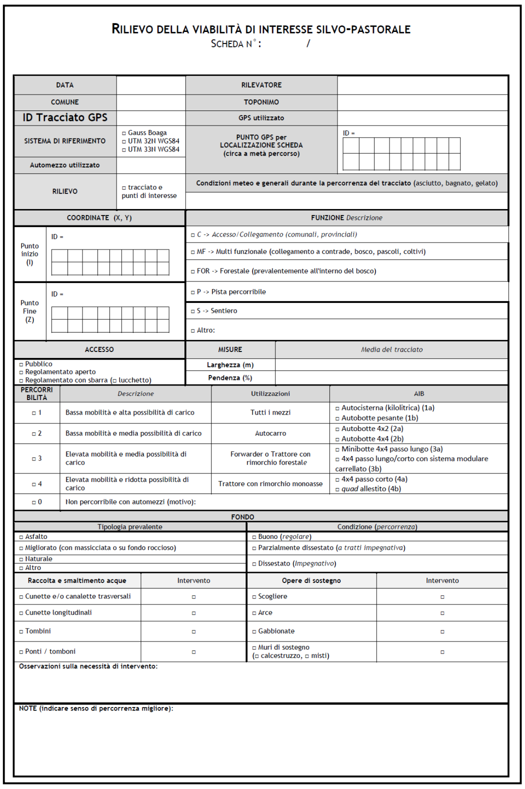
- the values of the 8 forest road density;
- the values of the indexes derived from the road density;
- the total extension of the forested areas;
- the ratio between the forested areas and the total area of the municipality;
- the mean slope of the forested areas (derived from the Digital Terrain Model at a resolution of 10x10)
- the surface included in the Management Plan
- the surface occupied from productive forest

The maps representing the indexes of road density present an indication regarding the anomaly of the values calculated for some municipalities situated in a marginal location respect to the mountainous area.
The territory of these municipalities is mainly in hilly condition with a high rate of agricultural lands and there is a large presence of private roads with the only function of access to residential or agricultural lands. This characteristic makes these territories of marginal interest for the purpose of the study.

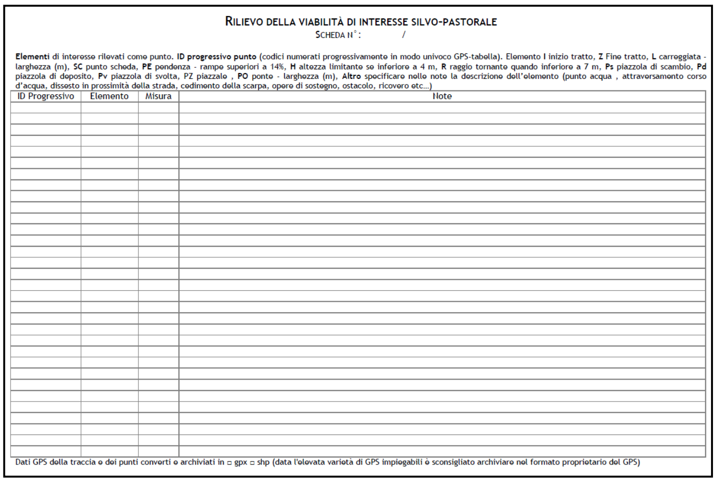
2.3.5. Protocol of survey and updating of the forest road geo-database

The continuous monitoring and the updating of the attribute table in the geo-database has a crucial role in order to increase the accuracy of the information about the forest road network and thus the possibility to use such information to support planning and management of the system.
To collect the information and update the attribute table of the forest road network *geo-database*, a a protocol of survey has been established.

For the collection of the data in the field A GPS receiver is used and two forms. The first form (Figure 9) is used to collect the information regarding the covered forest road in order to complete the attributes table. The second one (Figure 9b) regards the collection of the points of interest along each track. With point of interest, it is intended to mark each feature that can in some way be limiting for the transit (as a limiting width, an high slope, a localized damage) or important as infrastructure in executing forest operation (a landing, a turn point) or in forest fire defense. Where required to the point of interest is associated a measure (Table 7).



a)



b)

Figure 9 – Form for the collection of the information on forest road characteristic (a) and for the collection of the interest point along the road (b)

Table 7 - Type of interest point included in the protocol of survey and relative measure

CODE	Units	Description	Measure
I	-	Starting point of road	/
Z	-	End point of road	/
L	m	Width	Width of the road if limiting to the transit or in case of evident changing.
PE	%	Gradient	Gradient of the road if limiting to the transit or in case of evident changing. The point refers to the middle of the section of road
H	m	Limiting height	Height of the obstacle that limit the transit
R	m	Hairpin turn	Presenza di tornante. Se ritenuto si riporta la misura del raggio del tornante (in particolare se i raggi sono inferiori ai 5 m)
Ps	m^2	Passing bay	Dimension of the emplacement
Pd	m^2	Landing	Dimension of the emplacement

CODE	Units	Description	Measure
Pv	m^2	Turning area	Dimension of the area
Pz	m^2	Deposit landing	Dimension of the landing
PO	-	Bridge	
DIS	-	Road damage	Type: 1- Cut and fill slope weakness 2 - Surface problem (Rutting, potholes) 3 - Landslide 4 – Drainage system failure
Sbar	-	Presence of access restriction (bar, lock)	/
Al	-	Other point	Other points of interest

The two forms have been arranged and tested with the cooperation of the Forest Service of Belluno and Verona. The data survey and the updating of the geo-database are organized in the following steps:

- data collection using *consumer-grade* GPS receivers with mapping GIS functionality or professional receivers for mapping GIS survey with post-processing correction and filling of the survey form;
- export and conversion of the data into shapefile;
- overlapping of the new data with the existing data within the *geo-database*;
- updating of the information contained in the attribute table or addition of the track if missing.

The procedure of updating can be carried on from all the local authority (Comunità Montane), agency (Regional Forest Service) or stakeholders (forest fire defense corps, Civil Protection) that have the adequate competence.
The updating of the central geo-database could be scheduled with a horizon-time of 1 year. The control procedure to achieve a constant and homogeneous updating may consider the following actions (Figure 10):

- survey and data collection on the field at a local level;
- conversion of the track and of the point of interest into shapefile and storage;
- transfer of the data to the Central Regional Authorities (once a year), updating of the internal regional forest road geo-database from the Central Regional Authorities and re-transfer of the updated forest road geo-database from the Central Regional Authorities to the local authorities (Solution A);
- updating of the forest road geo-database directly at the Local Authorities and transfer of the updated forest road geo-database from to the Central Regional Authorities (Solution B).

After the achievement of a sufficiently accurate and complete level of the information, it is possible to publish the updated information in a WEBGIS portal for a complete sharing and accessibility.
8 sample areas have been identified within the analysis territory in different condition and geographic positions, locations where the protocol of survey have been tested (Figure 11). Inside these areas, the forest-road network has been completely surveyed and the geo-database has been updated with all the information.

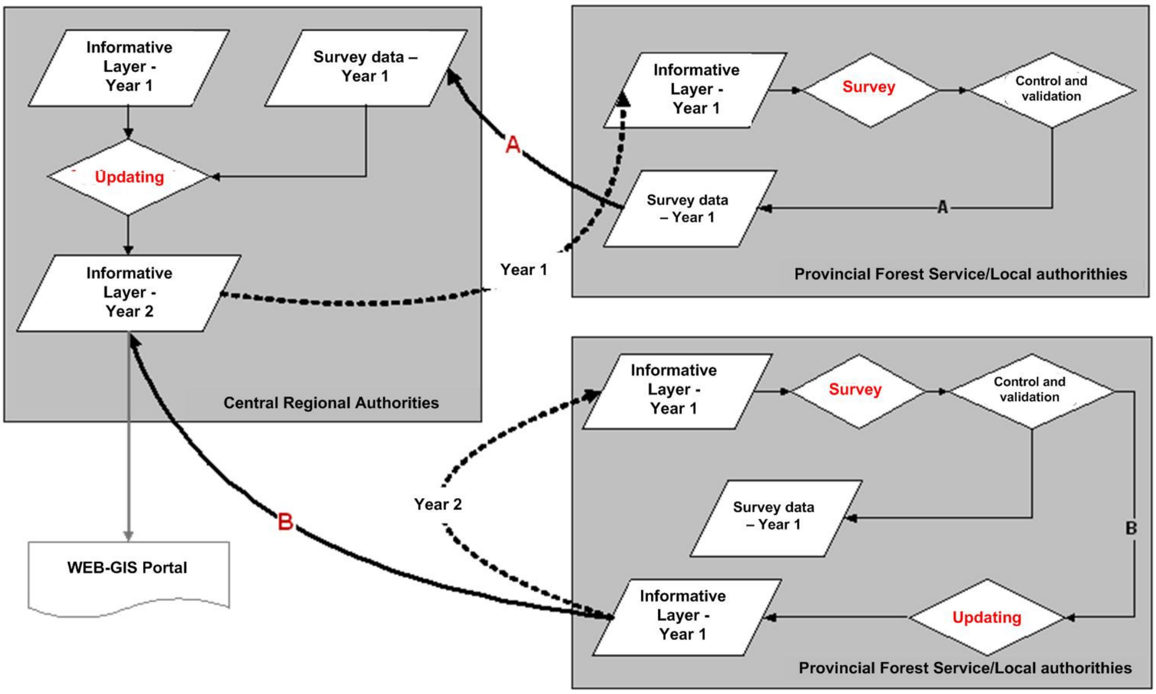


Figure 10 - Procedure for the updating of the geo-database in an annual basis

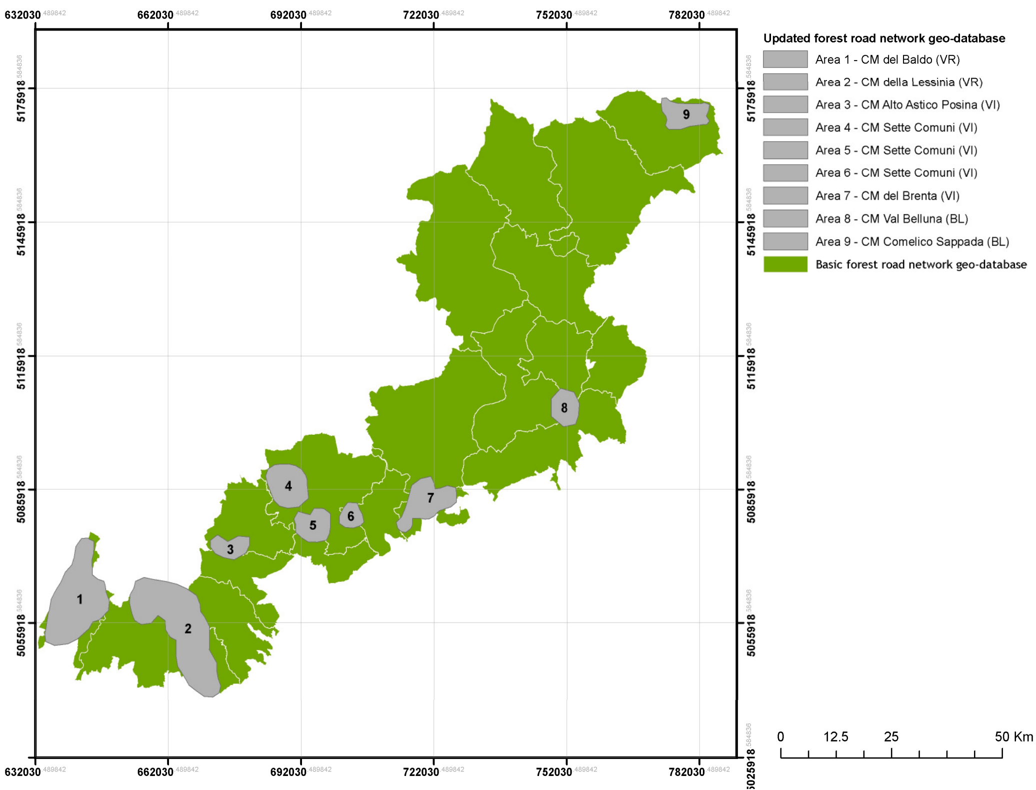


Figure 11 - Location of the surveyed areas

2.3.6. GPS tools

GPS receivers are frequently useful to forest management activities related with locating or mapping boundaries as monitoring harvesting machinery (McDonald et al., 2002), topography and cadastral forest surveys (Yoshimura et al., 2002), forest inventory, resources and special management areas (Wing and Kellogg, 2004), forest area and perimeter estimation (Tachiki et al., 2005) and GIS forest applications (Wing and Bettinger, 2003).
The use of GPS receivers is constantly increasing particularly because of the extended use of this technology in many outdoor recreational activities. Also the characteristics of the GPS receivers have evolved, becoming more accessible to a wide range of users and with prices often very cheap.
In analyzing the requirements of a GPS system for the survey of the forest road tracks the aspects taken into consideration were the accuracy, the portability and the simplicity of use.
The level of accuracy considered satisfactory for the purpose of the work is equal to 10 m, considering that the data will not be used for project or cadastral purpose.
The level of accuracy depends on the characteristic of the receiver and on the environmental situation in which it operates (number of visible satellites and their configuration). It is for example known that the positioning precision and accuracy under forest canopy are markedly lower than in areas with open sky condition because trees attenuate or stop GPS signals. The quality of the signal is expressed with the measure of the PDOP. With a greater number of satellites well distributed in the sky the PDOP value will be lower and the accuracy higher.
PDOP values lower than 6 can allow reliable measurements for all the purpose of GIS mapping and if the value is less than 4 the measures can be considered substantially accurate.
Although the application of the correction system WAAS-EGNOS or the differential correction procedures allow to notably increase the level of accuracy.
Second important aspect is the portability of the devices as often the paths are not easy to cover or present obstructions that force the operator to continue by walk.
Finally it is also important to consider the simplicity of use (easy and understandable menu options) and the quickness of the survey procedure. In particular the operator must be able to use the receiver after a short training.

a) b)

Figure 12 - Consumer-grade receivers with mapping GIS functionality (left) professional receivers for mapping GIS survey with post-processing correction (right)

Figure 13 - Application of an external antenna for Consumer-grade GPS receivers with differential correction (A) and external antenna with Bluetooth connection for Mapping-grade GPS receiver (B)

According to this characteristic GPS receivers can generally be classified into four types (
Figure **12**):

- professional receivers for topographic survey with real-time and post-processing correction (*survey grade*)
- professional receivers for mapping GIS survey with post-processing correction (*mapping grade*)
- *consumer-grade* receivers with mapping GIS functionality
- *consumer-grade* receiver without mapping GIS functionality

Survey grade GPS receivers are capable of determining locations within 1 cm of true positions (sub-metric precision) (Rizos 2002), but require operator expertise and a substantial operating budget because of the high costs of the instrument (from 15 000 €) (Bohrn and Stampfer, 2010). Survey grade GPS also require satellite signal reception that is often unattainable with forest canopy.

Mapping-grade GPS receivers with post-processing correction of the signal can return accuracies typically within 2-5 m of true position (metric precision), depending on the quality of the equipment and operator skill, with instrument cost ranging from 1500 to 11 000 €. Although mapping-grade GPS can be somewhat less demanding than survey grade in terms of acceptable satellite reception and required operator skill, the price of these units can be still high for many potential user. For these reasons the use of this kind of instrument seems to be not adept for the survey of the forest roads.
Consumer-grade GPS receivers with differential correction show an average error of 7-8 m. The cost of this type of GPS is about 400 €. This type of instruments can be considered suitable for the survey and the updating of the forest road geo-database both in terms of accuracy of the data both for the simplicity in their use and the relative low cost. In addition, for this type of device, through the use of freeware

software, it may be prepared and personalized to different types of thematic maps (forest type, forest road and trails, place name etc.) that considerably help during the survey process.

Consumer-grade GPS receivers without differential correction are now available at prices less then 200 € and there are many different manufacturers and styles. Manufacturers commonly assert that measurement accuracies of this equipment should be within 15-20 m of true position. Wing (2005) indicates that the positional accuracies of consumer grade GPS receivers are better than 15-20 m range often cited as a yardstick.
The use of *consumer-grade* GPS receivers without differential correction are not recommended for the survey and the updating of the forest road geo-database as the low precision of the acquired data does not guarantee a good result.
For all these GPS devices, it should be taken into consideration the possibility to use an external antenna placed outside the vehicles in order to improve the accuracy of the data (Figure 13).

2.3.7. GIS tools

Geographic Information Software has been used as support tools in the different phases of the work.
The functionality of a GIS can be subdivided into four main components or subsystems: data input, data storage and management, data manipulation and analysis, data output (Malczewski, 1999).

<u>Data input and editing</u>: data used in the present work to create the raw layer of forest road network have been imported from Technical Regional Map (.dxf format). Additional data was collected from GPS surveys (GPS points and tracks). All the data was converted into shapefiles (polylines and points features) and edited in order to gain the highest accuracy in the representation of the forest road network.
<u>Data storage and management</u>: data was organized in a *Geo-database* structure. The geo-database is a collection of geographic datasets of various types. *Geo-database* elements, are stored using tables. The spatial representations in geographic datasets are stored as vector features. These geometries are stored and managed in attribute columns along with traditional tabular attribute fields (ESRI, 2011).
<u>Data analysis</u>: to analyze the data the capabilities offered from the Toolbox implemented in Arc-GIS 10 have been used. This includes a large set of geoprocessing functions to take information from existing datasets, apply analytic functions and write results into new result datasets. Each geoprocessing tool takes existing information as input and derives a new result, which can be used in subsequent operations (ESRI, 2011).
<u>Data output</u>: maps representative of the data can be exported from the GIS environment in many different formats. Maps were normally printed as .pdf or image .jpg files.
Nowadays many different GIS software are available both with commercial licences or freeware or open source. Some of the commercial license GIS software are also developed *ad hoc* and exclusively for forest management.
The elaborations in the present work have been supported by the *commercial* GIS software Arc-GIS 10, developed by ESRI.
Most of the available free-ware GIS software present valid tools and processes for data management, editing, visualization and output. Major problems arise at the level of data analysis where open source GIS software often missed implemented tools or implemented tools are lacking because of software bugs. Consequently, the GIS-based analysis became more complicated or even impossible. In this case the limits of the use of open source GIS software could be solved by expert GIS users and programmers.

2.3.8. Evaluation of the quality of the information

Information contained in the "*Basic Forest Road Network Geo-database*" has been validated during field survey in order to evaluate the level of accuracy and then the possibility to be used for planning and operative purposes.

To evaluate the precision of the information, a comparison has been done from the characteristic of the roads ad indicated in the basic forest road network geo-database and the characteristic verified on the field. In the evaluation 5 type of possible errors have been considered as reported in the following table (Table 8).

Table 8 - Different type of error considered.

Error Code	Type of error
0	No error
1	Operative class overestimated
2	Operative class underestimated of 1 class
3	Operative class underestimated of 2 classes
4	Road not present on the terrain
5	Road present in the terrain and not in the *geo-database*

The influence of each error type has been evaluated as a percentage of km with wrong information respect to the total extension of the road network within the sample areas.

2.4. Results

2.4.1. Summary of the characteristic of the existing rural-forest road network of Veneto Region

Analyzing the information contained in the basic forest road network geo-database a first picture of the presence of the forest road network in Veneto Region have been extrapolated.

In the geo-database 15 670 km of road that can be considered of support for the agricultural and silvicultural activities in the mountainous region of Veneto in total has been included. To each of these roads a functional class and an operative class have been assigned.

Following figures shows the extension of the regional forest road network according with the two systems of classification (Figure 14, Figure 15).

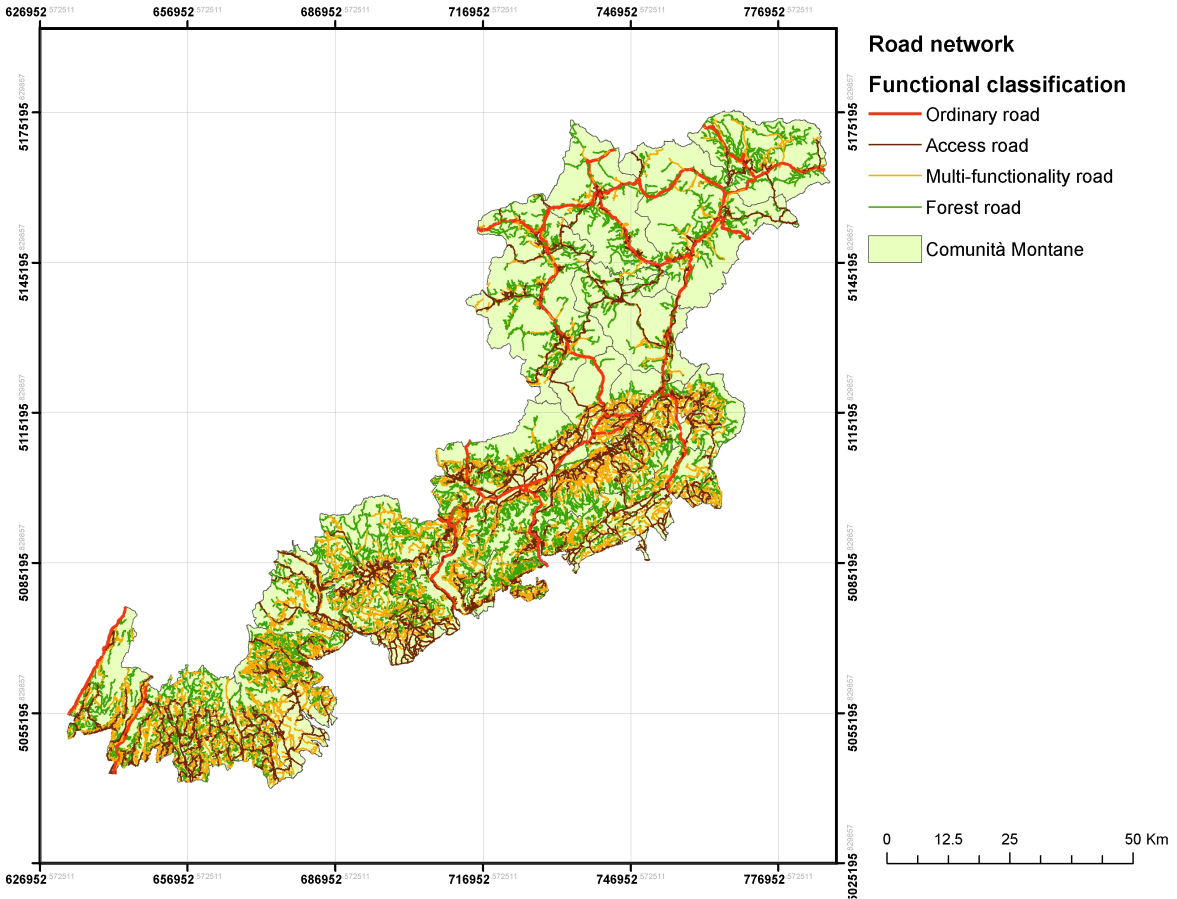


Figure 14 – Map representative of the functional classification of the forest road network of Veneto Region

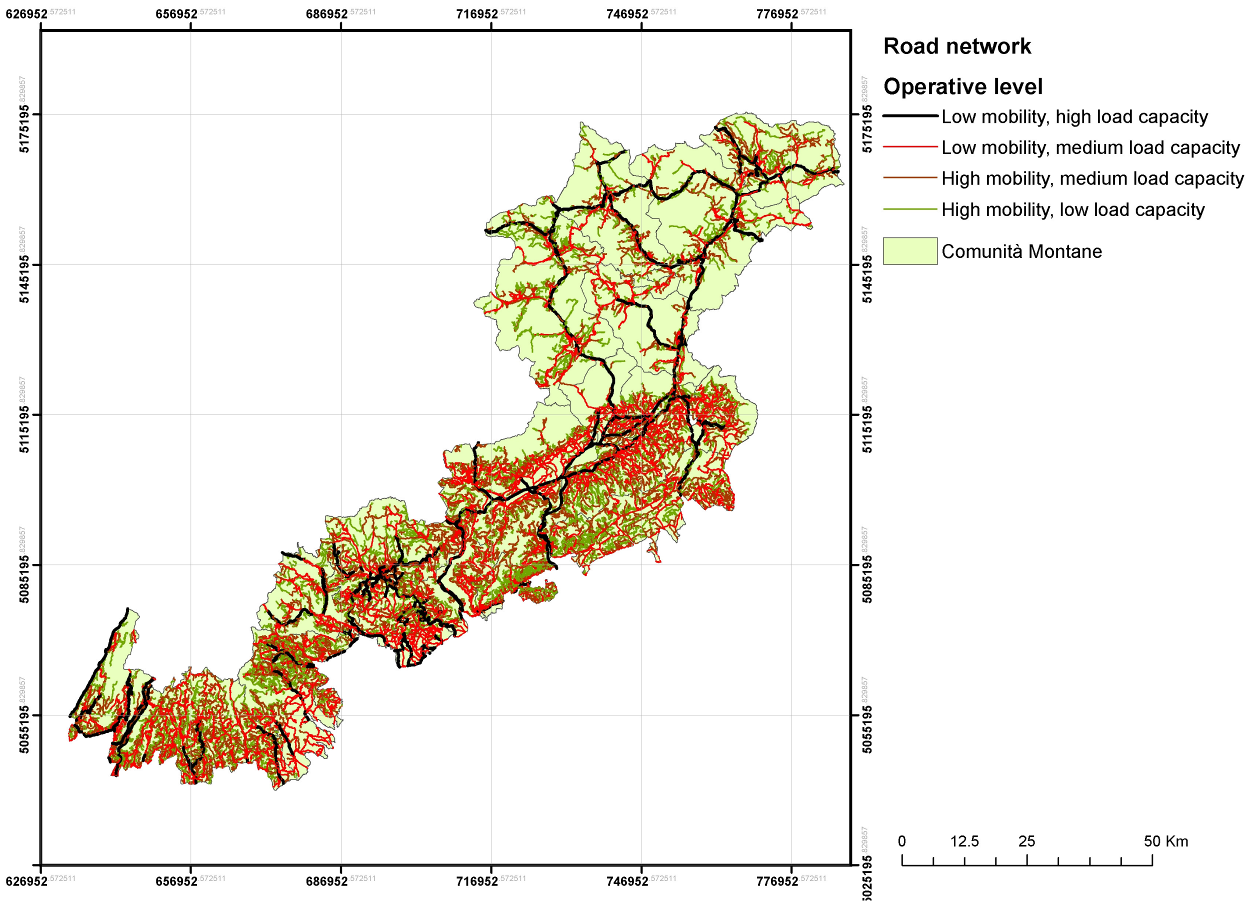


Figure 15 – Map representative of the operative classification of the forest road network of Veneto Region

Figure 16 and Table 9 resume the distribution of the forest roads included in the *forest road basic geo-database* into the different functional and operative classes considering the whole regional territory.

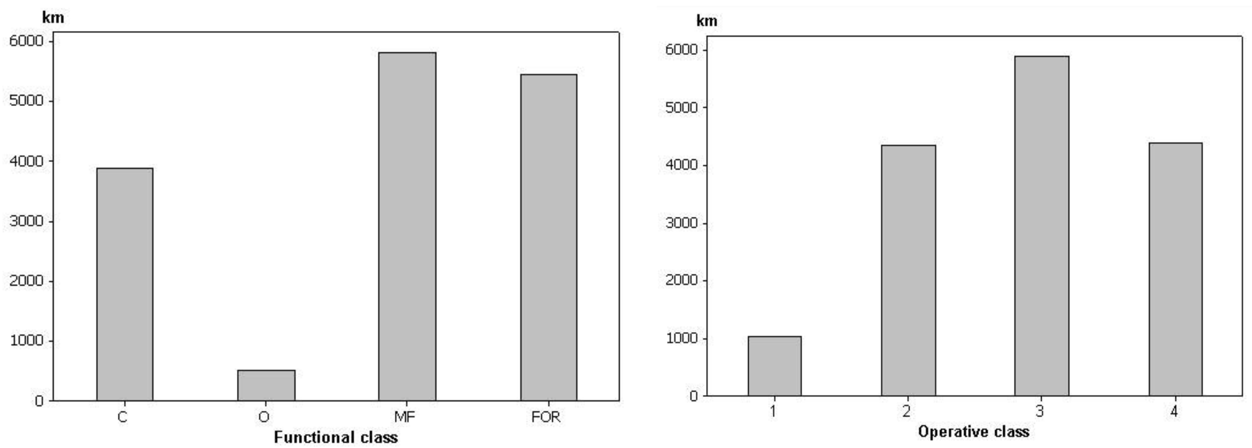


Figure 16 - Distribution of the forest road network in the functional and operative classes

Table 9 - Extension of forest roads classified according with the different functional and operative class

Functional Class	km	%	Operative Class	km	%
C	3882.44	36.32	1	1034.70	8.46
FOR	5457.84	23.23	2	4354.85	29.26
MF	5815.52	35.72	3	5892.34	38.66
O	514.3	4.17	4	4388.22	23.61
TOT	15670	100	TOT	15670	100

Have been also evaluated the distribution of the operative class of the roads according with their functional class (Figure 17,

Table 10).

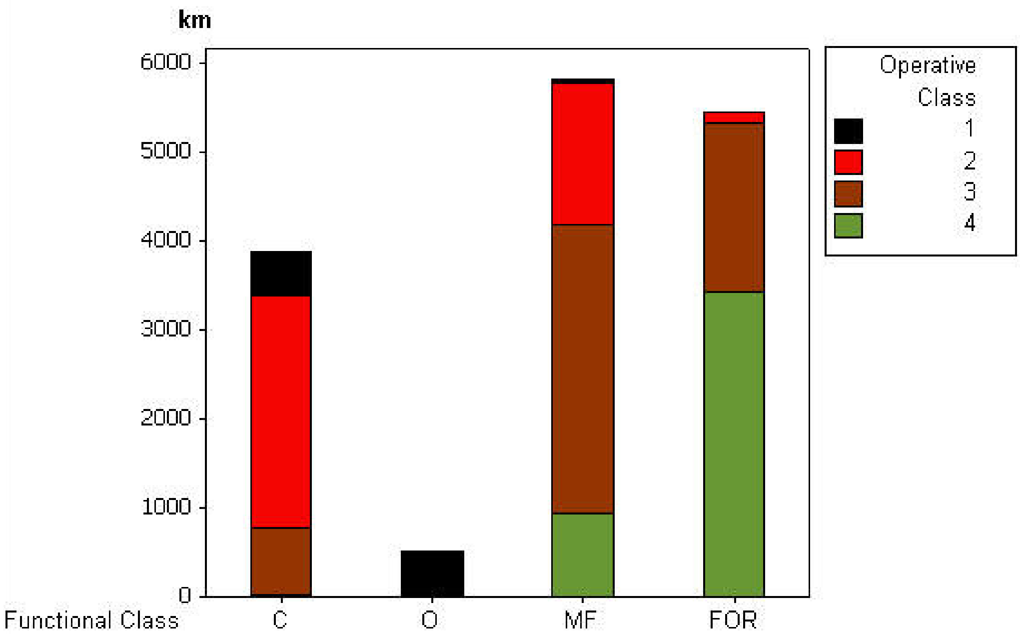


Figure 17 - Operative class of forest roads in function of the different functional class

Table 10 - extension of forest roads considering the combination of operative and functional class

Operative Class	1		2		3		4	
Functional Class	km	%	km	%	km	%	km	%
C	493.74	10.31	2621.58	62.39	749.83	26.87	17.27	0.42
O	505.67	98.44	7.88	1.5	0	0	0	0
MF	35.28	0.20	1593.49	17.33	3245.43	61.91	941.32	20.56
FOR	0	0	131.89	1.45	1896.32	29.19	3429.62	69.35

This distribution highlights that the most part (69%) of the exclusive forest roads (FOR) present an operative level of Class 4 (trafficability only for small vehicles) and the 30% present an operative level of Class 3 (trafficability for Forwarder). Multi-functional roads (MF) present an higher operative level with 62% of the road that are classified as Class 3 and 17% that present an operative level of Class 2 (trafficability for trucks). Access road (C) present an operative level of Class 2 in the 62% of their extension, 27% is included in Class 2 and 10% is included in Class 1.

Finally almost the entirety of the ordinary road (O) included in the geo-database present a trafficability for all the types of vehicles (Class 1).
All the data contained into the forest road network geo-database have also been summarized considering the different administrative units (Province, Comunità Montane and Municipality level) (Figure 18, Figure 19).

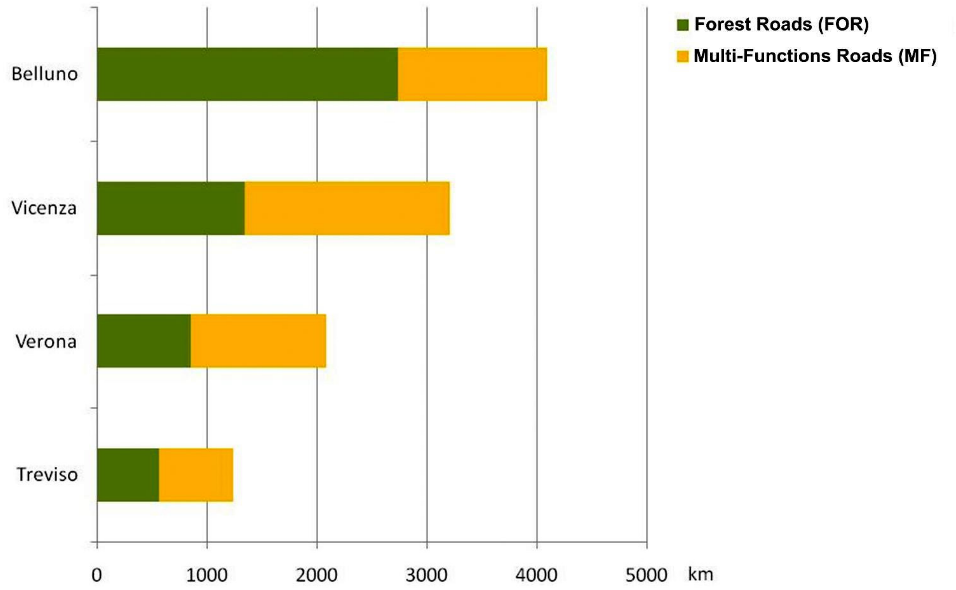


Figure 18 - Forest Roads and Multi-Function Roads extension aggregated for each Province

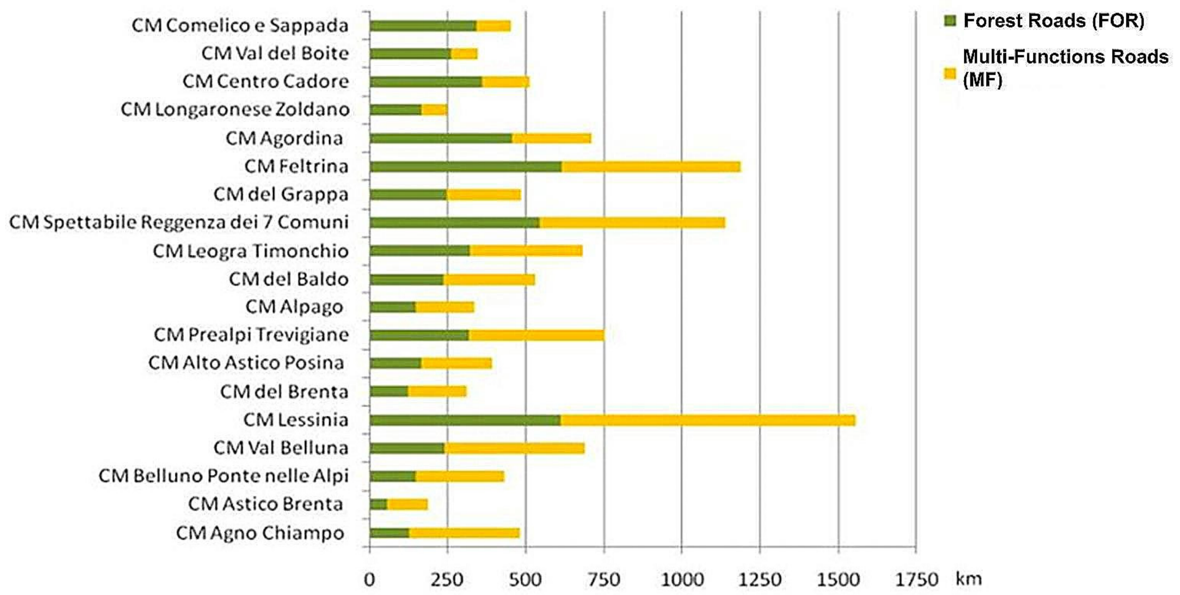


Figure 19 - Forest Roads and Multi-Function Roads extension aggregated for each Comunità Montana

__2.4.2. Summary of the density index__

The following tables report the Road Density value for each of the 8 class considered. The first one (Table 11) report the 8 road density values considering the whole mountainous area of Veneto Region.

Table 11 - Road Density Value for Veneto Region according to the 8 different density classification

	A	B	C	D	E	F	G	H
	m/ha	m/ha	m/ha	m/ha	m/ha	m/ha	m/ha	m/ha
Mean value for Veneto Region	30.5	20.2	19.0	11.3	13.3	7.5	9.7	7.3

Road density indexes have been calculated also referring to each Municipality (169) and Comunità Montana (19).
Table 12 reports the density indexes calculated for each Comunità Montana referring to the forested areas (SB) while Table 13 report the index referring to the managed surfaces (SA_T) and to the productive forest areas (SA_B).

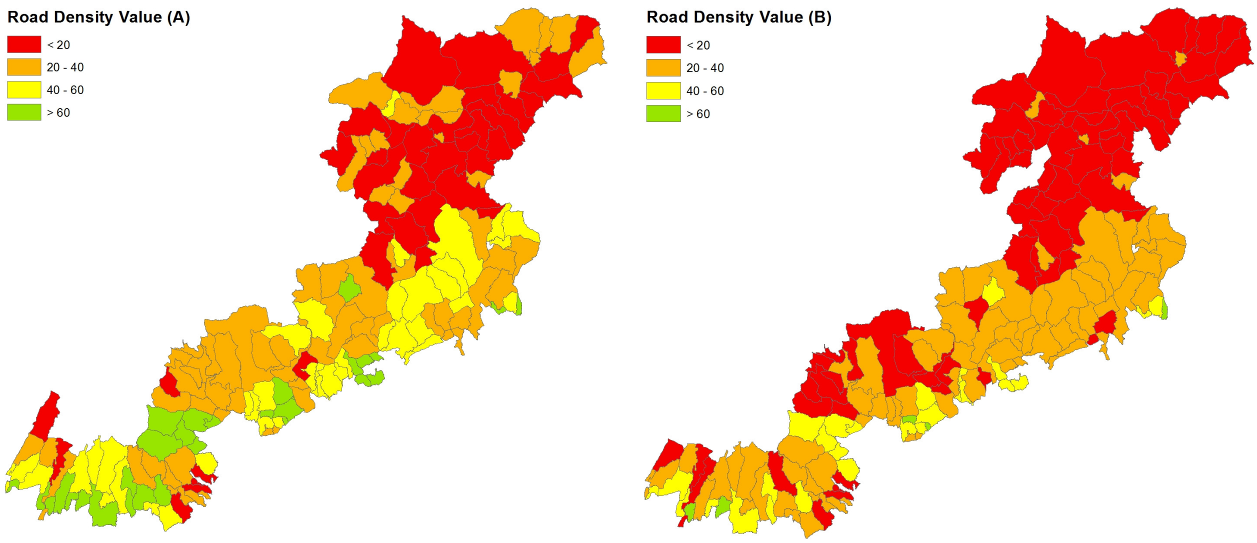
Table 12 - Density indexes of each Comunità Montana referring to the total forest surface

		SB	A	B	C	D	A	B	C	D
	Comunità Montana	ha	km	km	km	km	m/ha	m/ha	m/ha	m/ha
BL	CM Agordina	38936	806	415	536	208	20.7	10.6	13.8	5.3
BL	CM Bellunese-Belluno-Ponte nelle Alpi	10170	412	300	231	147	40.6	29.5	22.7	14.5
BL	CM Cadore Longaronese Zoldano	23798	358	283	235	171	15.1	11.9	9.9	7.2
BL	CM Centro Cadore	39324	585	353	423	234	14.9	9.0	10.8	6.0
BL	CM Comelico-Sappada	21270	455	320	284	188	21.4	15.0	13.4	8.8
BL	CM dell'Alpago	9371	345	247	203	130	36.8	26.4	21.6	13.9
BL	CM della Valle del Boite	22351	365	252	281	182	16.3	11.3	12.6	8.2
BL	CM Feltrina	37337	1296	979	873	632	34.7	26.2	23.4	16.9
BL	CM Val Belluna	20030	645	430	344	194	32.2	21.4	17.2	9.7
TV	CM del Grappa	6241	347	175	241	103	55.5	28.1	38.6	16.4
TV	CM delle Prealpi Trevigiane	21145	845	510	545	301	40.0	24.1	25.8	14.3
VI	CM Agno-Chiampo	12263	465	300	234	130	37.9	24.5	19.1	10.6
VI	CM Alto Astico e Posina	18547	458	291	295	162	24.7	15.7	15.9	8.7
VI	CM dall'Astico al Brenta	4557	210	172	101	73	46.1	37.8	22.2	16.1
VI	CM del Brenta	10061	310	249	193	148	30.8	24.8	19.2	14.7
VI	CM Leogra-Timonchio	10008	664	427	424	248	66.4	42.7	42.4	24.7
VI	CM Spettabile Reggenza dei Sette Comuni	30332	1045	685	695	413	34.4	22.6	22.9	13.6
VR	CM del Baldo	14460	461	309	269	162	31.9	21.4	18.6	11.2
VR	CM della Lessinia	24556	1238	770	613	348	18.8	31.4	25.0	14.2

Table 13 - Density indexes for each Comunità Montana referring to the total forested areas

		SA_T	SA_B	E	F	G	H	E	F	G	H
	Comunità Montana	ha	ha	km	km	km	km	m/ha	m/ha	m/ha	m/ha
BL	CM Agordina	44683	27384	380	129	287	82	8.5	2.9	6.4	1.8
BL	CM Bellunese-Belluno-Ponte nelle Alpi	4547	2988	48	30	35	21	10.6	6.6	7.6	4.6
BL	CM Cadore Longaronese Zoldano	20972	16028	142	100	116	79	6.7	4.8	5.5	3.8
BL	CM Centro Cadore	41130	26743	268	145	206	104	6.5	3.5	5.0	2.5
BL	CM Comelico-Sappada	25967	16887	342	228	231	153	13.2	8.8	8.9	5.9
BL	CM dell'Alpago	7678	4814	125	86	87	55	16.3	11.2	11.3	7.2
BL	CM della Valle del Boite	25379	18544	273	178	221	138	10.7	7.0	8.7	5.4
BL	CM Feltrina	12881	9922	183	134	131	97	14.2	10.4	10.1	7.5
BL	CM Val Belluna	11096	8837	91	52	75	41	8.2	4.7	6.7	3.7
TV	CM del Grappa	2477	2108	123	42	108	33	49.5	17.0	43.5	13.4
TV	CM delle Prealpi Trevigiane	4578	3942	107	56	86	42	23.3	12.3	18.9	9.3
VI	CM Agno-Chiampo	4633	4105	94	22	78	17	20.2	4.7	16.8	3.7
VI	CM Alto Astico e Posina	4897	3936	90	42	63	29	18.3	8.6	12.9	5.9
VI	CM dall'Astico al Brenta	1927	1417	59	45	36	27	30.4	23.1	18.5	14.1
VI	CM del Brenta	5726	4605	130	102	90	70	22.6	17.8	15.7	12.3
VI	CM Leogra-Timonchio	946	597	24	18	15	10	25.0	18.7	16.2	10.9
VI	CM Spettabile Reggenza dei Sette Comuni	30827	23819	747	450	502	284	24.2	14.6	16.3	9.2
VR	CM del Baldo	9067	7076	135	72	94	47	14.9	7.9	10.4	5.2
VR	CM della Lessinia	10082	7960	228	106	159	67	13.4	10.5	15.8	6.7

Following maps (Figure 20) shows as examples the Road Density value (DV) for the index A and B calculated at a municipality level.



a) b)

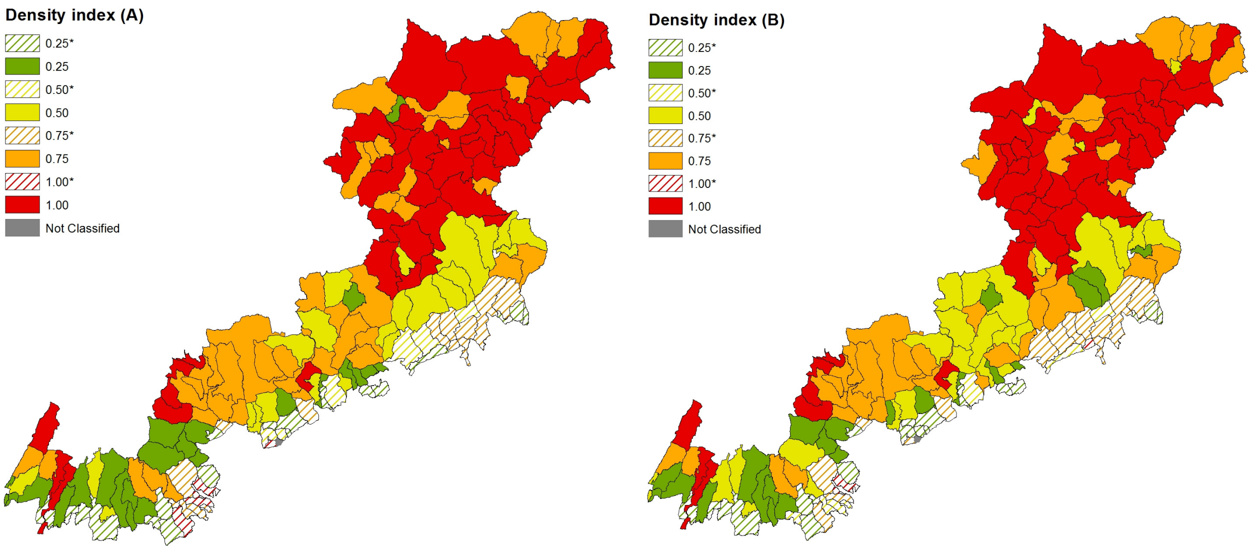
Figure 20 - Map of the Road Density Value (DV) for each municipality considering all the road (a) and considering only the road with operative Class 1, 2 and 3 (b)

The Road Density value (DV) is strongly influenced by the characteristics (extension of forested land, of the area, terrain mean slope) of the territory and is not suitable for the definition of a ranking of priorities at a Regional level that could be used for the allocation of the funds destined to the construction of new roads.
In order to make comparable the different road density values at a Regional level, statistical parameter of the density indexes of the 169 municipalities have been calculated (Table 14).

Table 14 - Statistical parameter of the density indexes calculated for the mountainous area of Veneto Region

	A	B	C	D	E	F	G	H
	m/ha	m/ha	m/ha	m/ha	m/ha	m/ha	m/ha	m/ha
Mean	39.0	26.3	22.3	13.3	18.2	10.5	17.1	9.2
Standard deviation	21.8	14.8	13.7	8.1	13.2	8.2	11.8	7.2
First Quartile	22.2	14.3	13.0	7.1	7.6	3.5	8.0	3.8
Third Quartile	53.0	35.0	27.7	17.1	27.5	15.1	23.3	13.1

An index equal to 1 indicates a municipality that is placed in the top quartile and therefore will take a priority position in the allocation of funds for the construction of new roads.
The use of this indexes (calculated both at a Regional level both at a level of Comunità Montana) allows to standardize the evaluation of the presence of roads making it more useful than the simple road density value (DV) in determining the presence of roads at such a large scale.
Following maps (Figure 21) show the value of some of the normalized indexes using the distribution of Road Density Values at the Regional level.



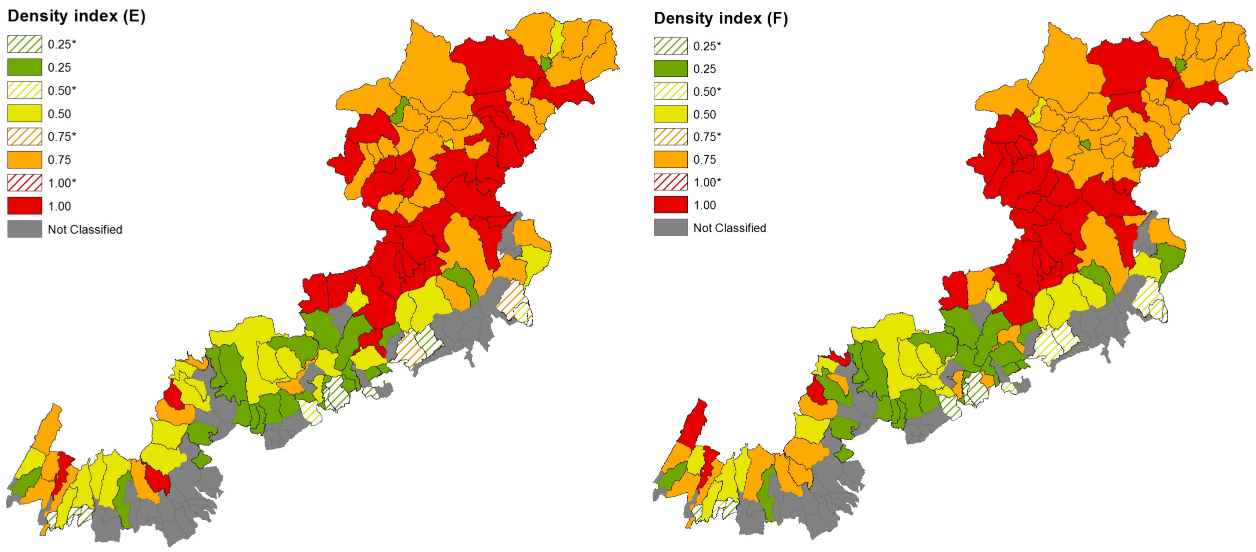


Figure 21 - Maps representing different normalized density index each municipality considering the statistical parameter calculated at a Regional scale

2.4.3. Results of the application of the survey protocol

To test the survey procedure developed in the present work and update the geo-database, between 2009 and 2011 were surveyed over 750 km of forest roads, subdivided within the different Province as reported in Table 15.

Table 15 - Extension of surveyed forest road network

Province	km	Year
Belluno	120	2009
Treviso	155	2010-2011
Vicenza	240	2009-2010
Verona	260	2010
TOTAL	775	

The field survey lead to the production of a much more detailed informative layer where the attribute table of all the features are populated with the required information and the inaccuracies present in the *Basic Forest Road Network Geo-database* are fixed.

In the new informative layer to each road are then associated many information useful for its management. Just clicking on the road features is possible to know the most important characteristics (Figure 22), such the type of surface, the condition of the surface, the presence and the condition of the drainage system, the type of access. Additionally information to define the trafficability limits such the mean width and the operative class are present in the database.

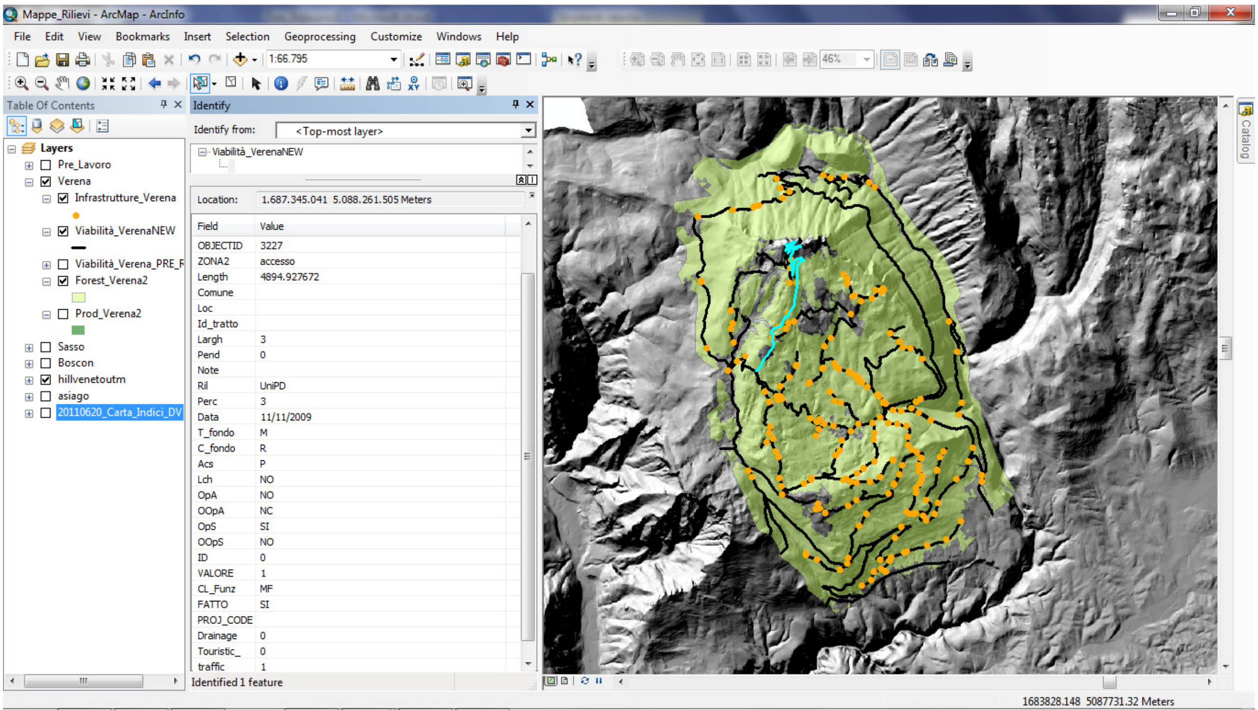
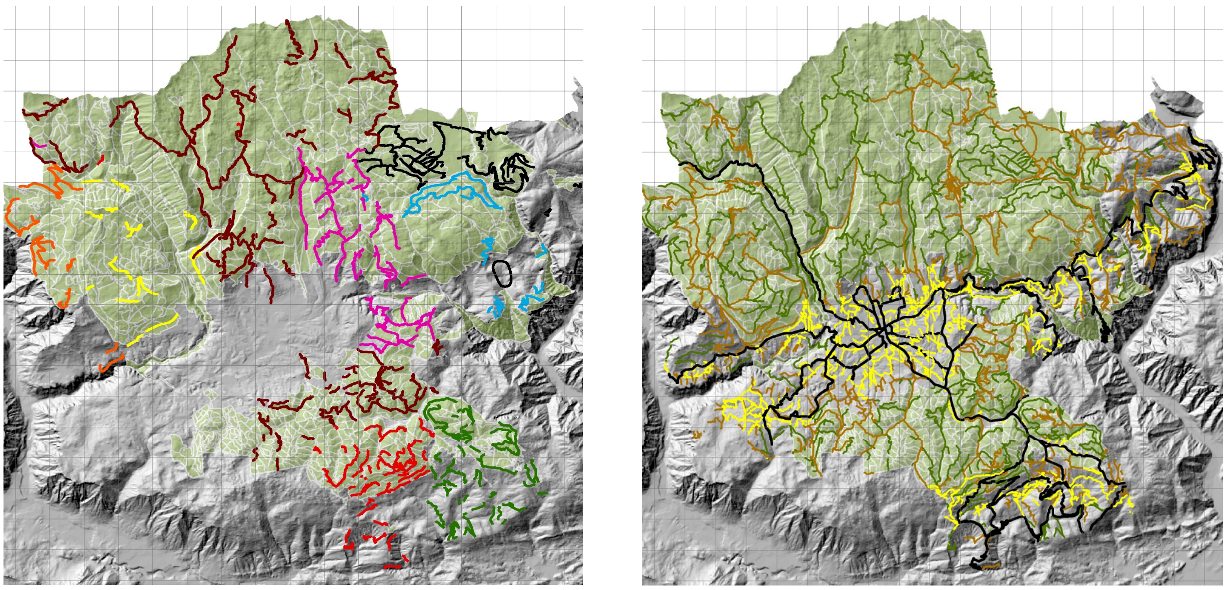


Figure 22 - Example of the information contained in the updated forest road network geo-database

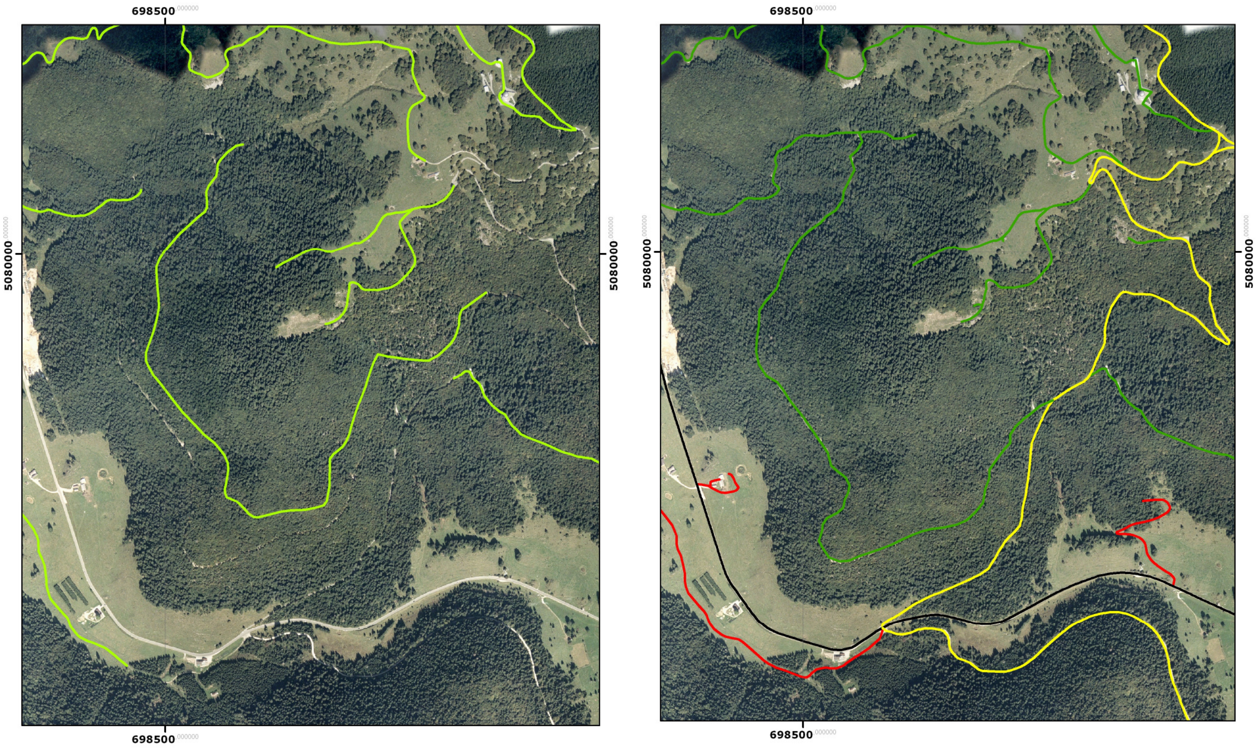
Figure 23 displays the informative layer representing the forest road network owned from the management authorities before and after the predisposition of the B*asic Forest Road Network Geo-database*.



a) b)

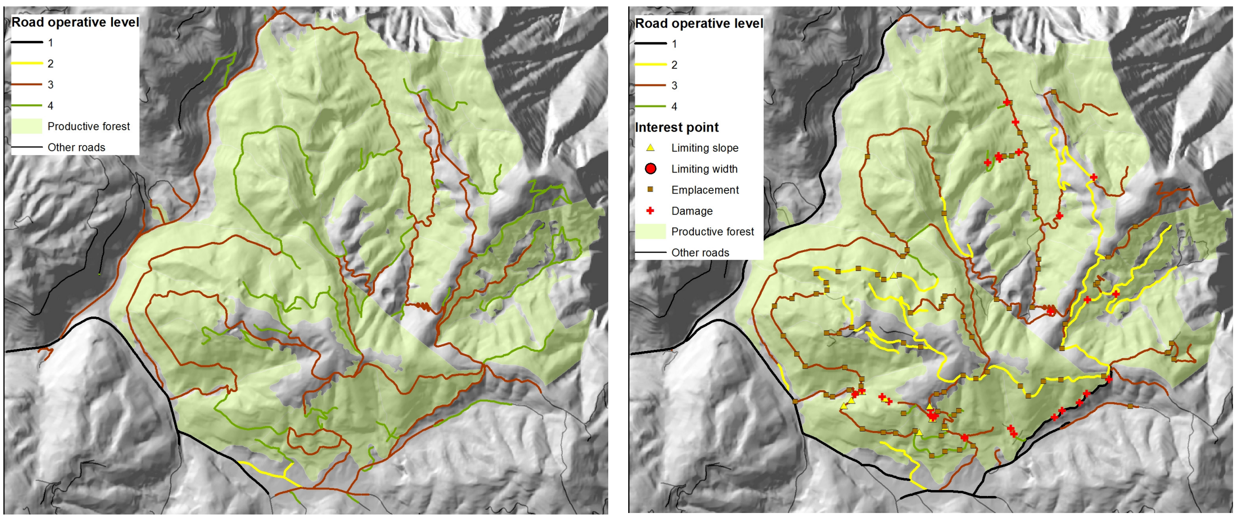
Figure 23 - Difference between informative layer of forest road network hold from the management authorities(a) and informative layer contained in the forest road network basic geo-database (b) for the Comunità Montana "Spettabile Reggenza dei Sette Comuni"

Figure 24 highlights the presence of errors in the previous information layer owned from the management authorities (Figure 24) and the informative layer after the complete survey in the field.



a) b)

Figure 24 - example of common errors present in the existing informative layer and the same area as represented in the new forest road network geo-database



a) b)

Figure 25 - difference between the map displayed using the information contained in the *basic forest road network geo-database* and the same area after the field survey (*operative forest road network geo-database*)

Finally, the reported difference between a real-situation before and after the field survey (Figure 25) where it is evident the underestimation in the first case.
The new level of information can be used as a basis both for operative purpose (eg. forest operation or forest fire defense organization) both for planning (evaluation of the accessibility and needs of new forest roads).

2.4.4. Evaluation of the quality of the information

The evaluation of the difference from the presence and the characteristic of the forest road indicated in the basic forest road network *geo-database* and the presence and the characteristic verified on the field are reported in the following table (Table 16) according with the type of difference that have been noticed.

Table 16 - type and magnitude of the error noticed in the basic forest road network geo-database

	No Error	Error 1	Error 2	Error 3	Error 4	Error 5	Error 6	Tot
km	113.53	3.52	97.22	17.50	-	-	7.32	239
%	47.50	1.47	40.68	7.32	-	-	3.06	100.00

The roads that were included in the geo-database were the 97 % of the total highlighting a good correspondence with the real situation in the localization of the roads.
Moreover in the 47.5 % of the surveyed road there was complete correspondence between the information contained in the basic forest road network geo-database and the reality. The most common error was due to the underestimation of the operative class of the road that occurs in the 40 % of the roads. This type of error was expected as during the classification of the road in the office in case of uncertainly the assigned operative class was voluntarily underestimated.

2.5. Conclusions

The creation of a cadastre of the forest road network for Veneto Region represents the first tool in order to achieve an informative level that can support a well-oriented management strategy.
The collection and organization of all the information in such an extended area was a laborious and time-consuming work but it was necessary in order to achieve an unique and standardized information about the regional forest road network.
The information contained in the "*Basic Forest Road Network Geo-database*" provides a first informative level that has been used to estimate the extension of the road network system and to elaborate statistic on a large scale. The estimation of a statistical index of the forest road density can be considered a valid methodology to evaluate the presence of forest roads at a municipality level and to rank the projects in founding sharing decision.
The evaluation of the precision suggests that the information about the operative classification contained in the "*Basic Forest Road Network Geo-database*" are not enough accurate to be used in an operative level, such for example for the organization of the forest operations or to plan forest fire defense operations. This is mainly due to the limited information contained in the available cartography. The roads that were included in the geo-database were instead the 97 % of the total highlights a good correspondence with the real situation in the representation of the road network.

The application of the field-data survey protocol in the sample areas shows that the use of consumer GPS receivers with mapping functionality represent a sufficiently quick and precise method for the collection of the information and the updating of the existing geo-database.
The "*Operative Forest Road Network Geo-database*" has been completed for about 750 km of road. The result of this pilot application and the potential use of the acquired information represent a good example for all the stakeholders inside the Region to carry-out the collection of the information for all the mountainous territory of Veneto Region.
In conclusion, the result obtained can be considered satisfactory, especially considering the uniformity of the data and the achieved level of detail compared to the one of the previous information hold from the management authorities.
The following step will then regard the development of GIS-based decision support tools, that will use in an effective way the data contained in the *geo-database*, moving from an informative level to an operative one through data analysis and elaboration.

Chapter 3: GIS-based models to support decisions in forest road network planning and management

3.1. Geoprocessing and Arc-GIS Model-Builder

Geoprocessing is the methodical execution of a sequence of operations on geographic data to create new information. The two fundamental purposes are to perform modeling and analysis and to automate GIS tasks (ESRI, 2011).
Geoprocessing often involves the design and execution of one or more models. In many instances pre-existing models or simple variants of these are used. Such models may be provided within standard GIS packages, or they may be offered by third parties as add-ons, or they may have been specially developed for specific applications (De Smith M.J et al. 2011).
With geoprocessing, it is possible to automate many GIS tasks, such as data preparation and conversion or automation of data management and analysis workflows for map production. These workflows are repeatable and self-documenting and they can be shared with many users.
In the present work, the model has been implemented using Arc-GIS Model-Builder (ESRI, 2011).
Model-Builder provides a graphical modeling framework (Figure 26) for designing and implementing geoprocessing models that can include system tools, scripts, models, and data.

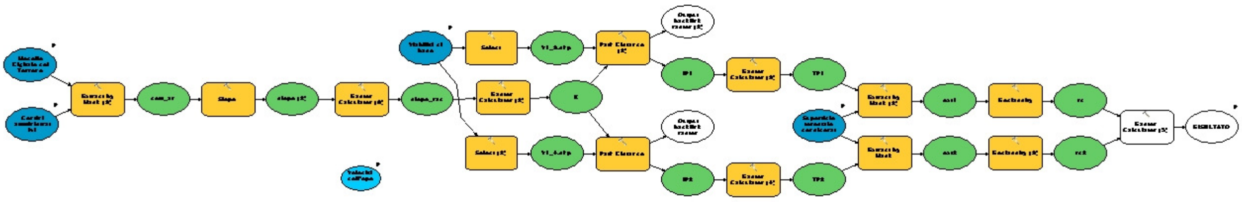


Figure 26 - Example of Model-Builder graphical layout

Model-Builder is an application used to create, edit, and manage models. Models are workflows that string together sequences of geoprocessing tools, feeding the output of one tool into another tool as input. Model-Builder can also be thought of as a visual programming language for building workflows.
While Model-Builder is very useful for constructing and executing simple workflows, it also provides advanced methods for extending Arc-GIS functionality by allowing you to create and share your models as tool (ESRI, 2011).
The ultimate objective of a model is, or should be, to improve planning and decision making processes by providing useful and scientifically sound information.

3.2. GIS-based tool to evaluate the accessibility of the territory (FORACCES)

3.2.1. Purpose of the model

The purpose of the model FORACCESS is to evaluate the accessibility of the territory. The evaluation is based on the determination of the time that an operator takes to reach a determined point in the forest starting from the road-side, considering the geo-morphologic characteristic of the terrain.

3.2.2. Basics of the model

The evaluation of the buffer area along a road can be determined through GIS-based procedures that use different approaches. The simplest one uses only a buffering operation, which define bands of accessible areas of constant amplitude and symmetrical respect to the road center. A more complex buffering methods take into consideration other variables related to the geo-morphologic characteristic of the terrain or economic evaluation. In this case, the amplitude of the accessible bands will vary based on these variables.
The methodology used in this study to determine the accessibility of the forest refers to the methods proposed by Hippoliti (1976) based on the determination of the time that an operator takes to reach a determined point in the forest starting from the road-side.
An area can be considered easily accessible when it is reachable within a time of 30 minutes go and back, poorly accessible with a walking time within 60 minutes go and back and not accessible up to this value.
The methods proposed by Hippoliti (1976) has been already studied and adapted to GIS-based analysis by Floris et al. (1999) and Chirici et al (2003).
The parameters into the model are the linear distance from the road-side and the difference in height from the starting point and at the end of the process the forest area will be indexed according to the walking-time.
The distance from the road (linear distance) and the height difference is calculated using the Digital Elevation Model GIS through a function for calculating the cumulative distance (Distance Path). This function can in fact handle more variables and assign different weights depending on the geo-morphological characteristics of the terrain.

The <u>inputs</u> of the model are as follows (Figure 27):

<u>Forest road network geo-database (polylines features):</u> the model allows to choose the forest road network to consider for the analysis. The attribute considered is the operative class that is used to determine the level of accessibility according with the existing type of road and thus indicate the possibility of improvement.

<u>Digital Terrain Model (raster):</u> used to create the slope-map base for the determination of the increasing-index of the accessibility time. High resolution data guarantees more precise results with higher elaboration-time.

<u>Administrative boundaries (polygon features)</u> and <u>Analysis area:</u> boundaries of the administrative area (Region, Province, Municipalities) and of the analyzed area (forest, area from the management plan,

productive forest) in which is intended to run the model. The model use the polygons as extraction masks for the other input data to limit the elaboration time

Speed of the operator: define the speed of the operator in normal (flat) condition (m s^{-1}).

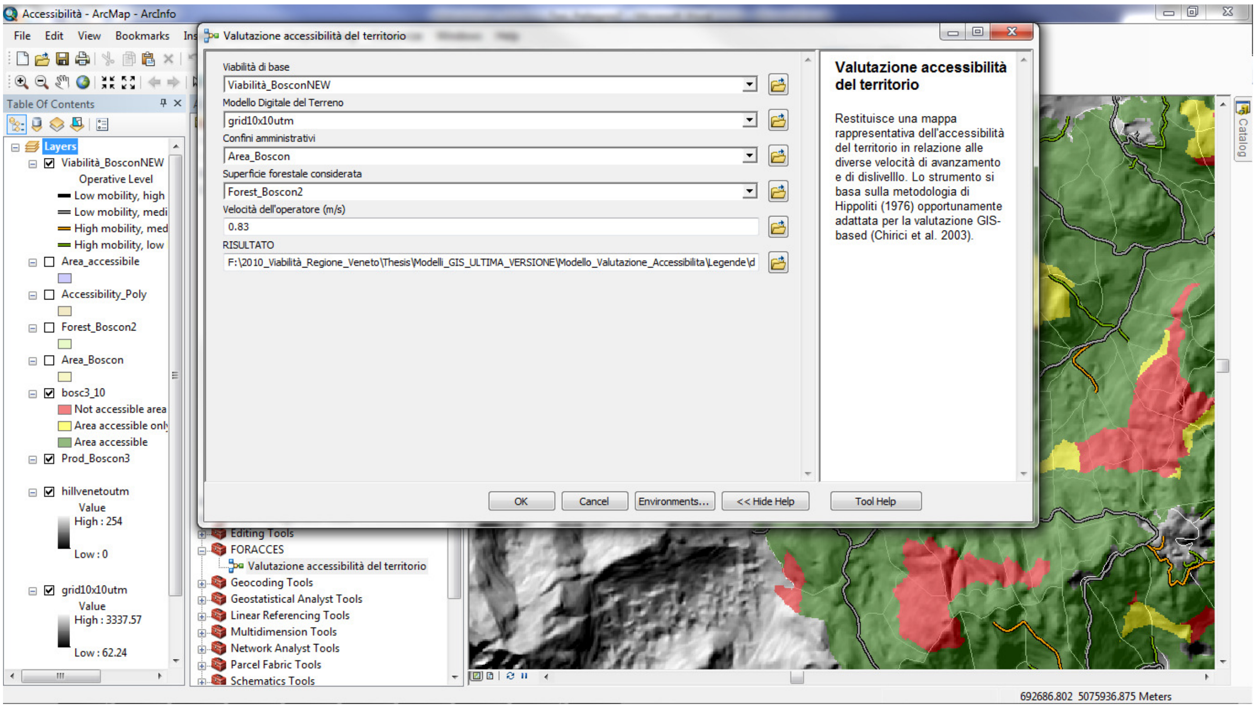


Figure 27 - Input mask of the model FORACCESS

3.2.3. Describing process of the model

Firstly, the forest road network (first input data) is clipped (*clip tool*) using the administrative boundaries polygon (second input data). The same polygon feature is used to extract (*extract by mask tool*) the part of interest in the Digital Elevation Model (third input data).
The extracted forest road network passes through a selection procedure (*select by attributes*) that uses the functional and operative classification data contained in the attributes table. After the selection, the road network is divided in two groups according to the operative function. The first group contains all those roads that allow the transit to vehicles with carrying capacity (operative class 1, 2 and 3), the second contains the roads with operative class 4, that can be practicable only for small vehicle.
A parallel process involve the extracted DEM from which is calculated (*slope tool*) the raster representing the slope of the terrain (in degree). Using the *raster calculator tool* the slope value is converted into radiant (measures unit used for the calculation).
Slope in radiant (Prad) represents the input in the following calculation of the increment index of walking time (K) that is the core of the model. To determine the index K the following formula is used, derived from the increasing of time to cross one cell at the increasing of the slope of the terrain:

$$K = 1.173 * \exp^{2.6966 * Prad}$$

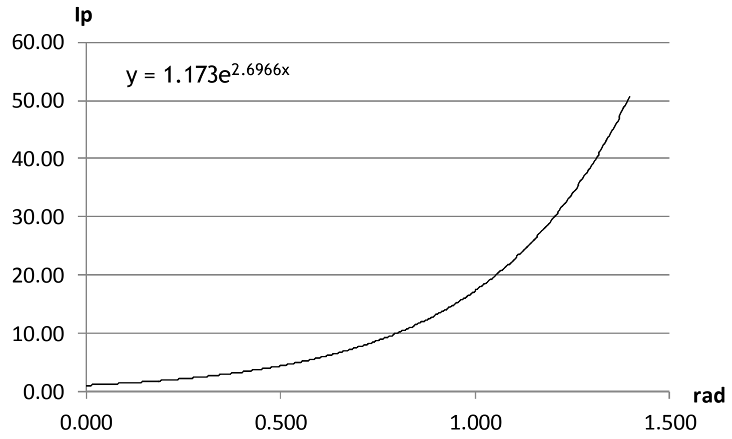


Figure 28 - Trend of the increment index of travelling time as a function of the slope of the terrain (rad)

The expression of the increment is implemented in the model using the raster calculator.
The raster representing the value of K is used as an input cost raster in the calculation (Path Distance Tool) of the Operator Travel Index (OTI) that represents a hypothetical distance that includes the slope factor. The OTI is divided for the speed of the operator to calculate the cumulated travelling time (TP). The speed of the operator is defined by the user (indicative values are provided).
All the operations following the calculation of K are performed for each of the two forest road network subdivisions.
The two raster maps representative of the cumulated travelling time are then classified into 3 classes (reclassify tool) according to the classification methods proposed by Hippoliti to evaluate the accessibility of a surface.
The two reclassified raster maps are then summed to get the final map, representative of the accessibility of the territory that can be extracted (extract by mask) for the area of analysis (fourth input data).
The accessibility of the territory is thus evaluated using three classes. The areas that are easily accessible are those parts of the territory where the forest road network is enough to correctly perform the management.
In the areas accessible using roads with an operative class 4, the possibility to upgrade the existing forest road network according with the needs of the management strategies should be evaluated.
Finally, in the areas that resulting as not accessible, the possibility to create a new road should be considered if the management strategies would require access to the area.
Figure 29 shows graphically the logical process used in the model.

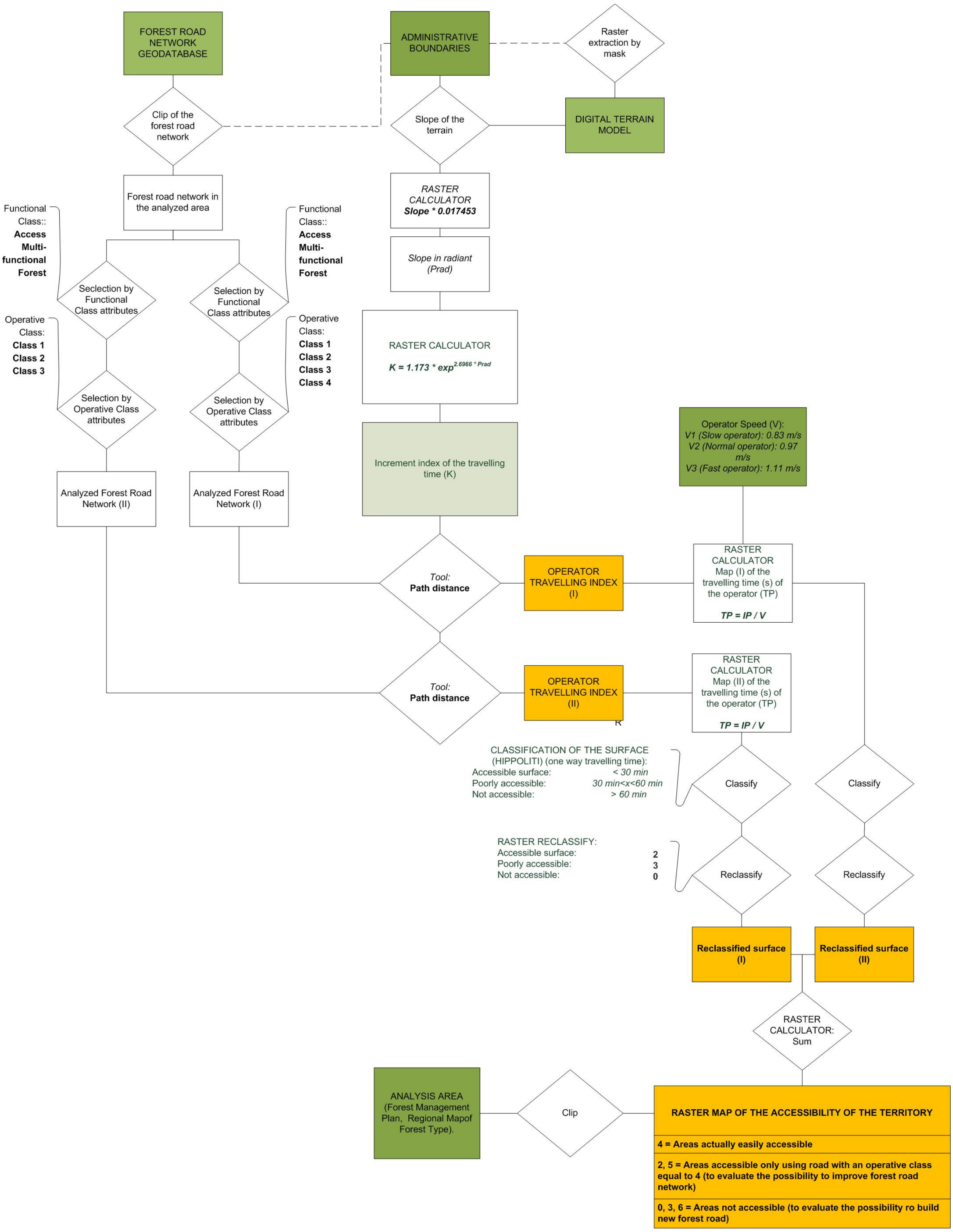


Figure 29 - Logical process of the model of evaluation of the accessibility of the territory (FORACCESS)

3.3. GIS-based tool to evaluate the suitable wood extraction system (FORSE)

3.3.1. Purpose of the model

The purpose of the model FORSE is to produce a map representing the technically feasible area for each wood extraction system while considering the geo-morphologic characteristics of the terrain and the operative classification of the road network.

3.3.2. Basics of the model

Accessibility is the most critical factor influencing feasibility and logistic of operations in mountainous terrain.

The terrain slope, together with the structural characteristics of the forest and the roughness of the terrain, are the determining factors in the choice of the system of extraction. Moreover the various systems of extraction have limits in application also in relation to the distance from the road.

To evaluate the needs of forest roads of an area, it is fundamental to evaluate together with the accessibility of the forest also the possibility to perform the silvicultural operations.

In fact, while the forest road network allows access to the forest area, the system of extraction can be considered the limit which defines the part of forest that can be managed with the present roads.

Transportation can be divided in two phases, off-road and on-road, which are heavily interdependent on the conditioning from the characteristics of the forest road network and the conditions of the terrain.

There are four principal means of off-road transportation: ground vehicles on natural terrain, ground vehicles on skid roads, carriages on cable structures and airships in the atmosphere (Heinimann, 1999).

Terrain slope is the most significant parameter in influencing the off-road transportation and consequently the choice of the extraction system. Vehicles can move on the terrain only where the slope is not too high.

Another factor that affects the applicability of the ground-based systems is the roughness of the terrain. Where terrain conditions become too difficult, cable structures enable the transport of partially or fully suspended loads over large distances, avoiding various terrain obstacles.

Wood extraction techniques are also strictly connected with the presence and the characteristics of the forest road network. The forest road and its operative level represent the starting point for any forest operation. For this reason, it is important to take into consideration the operative level of the road to access the working site.

Running the model FORSE, the analyzed areas will be categorized considering 4 types of extraction techniques. The model considers the 4 systems more commonly used in the region. 2 of those systems are ground based systems, one representative of a high level of mechanization (off-road transport using forwarder and possibility to combine it with the harvester) applicable where the condition both of the terrain and both of the road network are optimal and one system (tractor and winch) applicable where the condition of accessibility became difficult but the terrain still allows the use of ground-based machines. The other 2 systems involve the use of mobile cable cranes. Table 17 reports the extraction systems considered in the model and the adopted limits.

Table 17 - Considered extraction systems and their limits

	Range of slope downhill (%)	Range of slope uphill (%)	Max distance (m)	Type of access road
Ground based extraction using tractor and winch	0-35	0-20	350	Class 4
Ground based extraction using forwarder	0-30	0-20	500	Class 3
Extraction using small-size mobile cable-crane	20-100	20-100	400	Class 3
Extraction using medium-size mobile cable-crane	20-100	20-100	800	Class 3

<u>Ground based extraction using tractor and winch</u>: represent still one of the most used methods in Italian forest enterprises because tractors are cheap and may be adapted to forest use with very few adjustments. Agricultural 4WD tractors are usually modified by adding protection to wheels valves, increasing front weight and mounting chains (Cavalli 1997).

The tractor is especially useful in the situation where the access road presents characteristics that allow transit only by small machines. The terrain maximum slope is different according to the skidding direction (uphill or downhill) and if moving with or without loads. Moving uphill, the maximum slope is about 10-20%, up to 35% if driving unloaded, with a maximum of 40% on very short road tracks. Moving downhill the maximum slope is 35%.

The maximum extraction distances, within which the productivity of tractor is not badly influenced, can be considered between 300 and 500 meters.

<u>Ground based extraction using forwarder</u>: where the type of access road allows transit using bigger machines, the use of the forwarder became feasible.

As other off-ground machines, the forwarder's technical limits depend on the terrain slope, roughness and extraction distance. The uphill extraction is feasible on slopes up to 25-30%, while skidding downhill slopes may reach 35%.

The terrain roughness has less influence on the forwarder than the tractor because the forwarder's frame is higher from ground (more than 60 cm) due to the wheel configuration and hydraulic system.

The maximum extraction distance, within which the productivity of the forwarder is not badly influenced, can be considered between 400 and 600 meters.

<u>Extraction using small-size mobile cable-system</u>: the mobile cable cranes are the simplest, cheapest and most rapid to install aerial skidding systems. The working sites require enough space to set up the tower and piling logs. Moreover, an access road with a good operative level is required to access the site with the machine. The maximum distance for this type of system is about 400 m while the slope of the terrain should be higher than 20% with a maximum slope of 100% (Cavalli and Menegus, 2003).

<u>Extraction using medium-size cable-crane</u>: the long mounting and dismounting times first cause a productivity reduction that makes it possible to use this system only with intense and well distributed cutting that compensates the low productivity and the high unit costs.

Even in this case, the working sites as well as the access road need to be at a good level in order to guarantee the access to the site and the rational organization of the operation.

The maximum distance for this type of system is about 1000 m while the slope of the terrain should be higher than 20% with a maximum slope of 100%.

The <u>inputs</u> of the model are (Figure 30):

<u>Forest road network geo-database (polylines features):</u> the model allows the selection of the forest road network to for each extraction system considering its operative classification.

<u>Digital Terrain Model (raster):</u> used to create the slope-map and then define the range of slope within each extraction system is feasible. High resolution data guarantee more precise results with higher elaboration-time.

<u>Administrative boundaries (polygon features):</u> boundaries of the administrative area (Region, Province, Municipalities) in which is intended to run the model. The model uses the polygon as extraction mask for the other input data to limit the elaboration time.

<u>Analysis area:</u> boundaries of the area (normally represented from the productive forest areas) in which the model is intended to run. The model uses the polygon as an extraction mask at the end of the process to display the results.

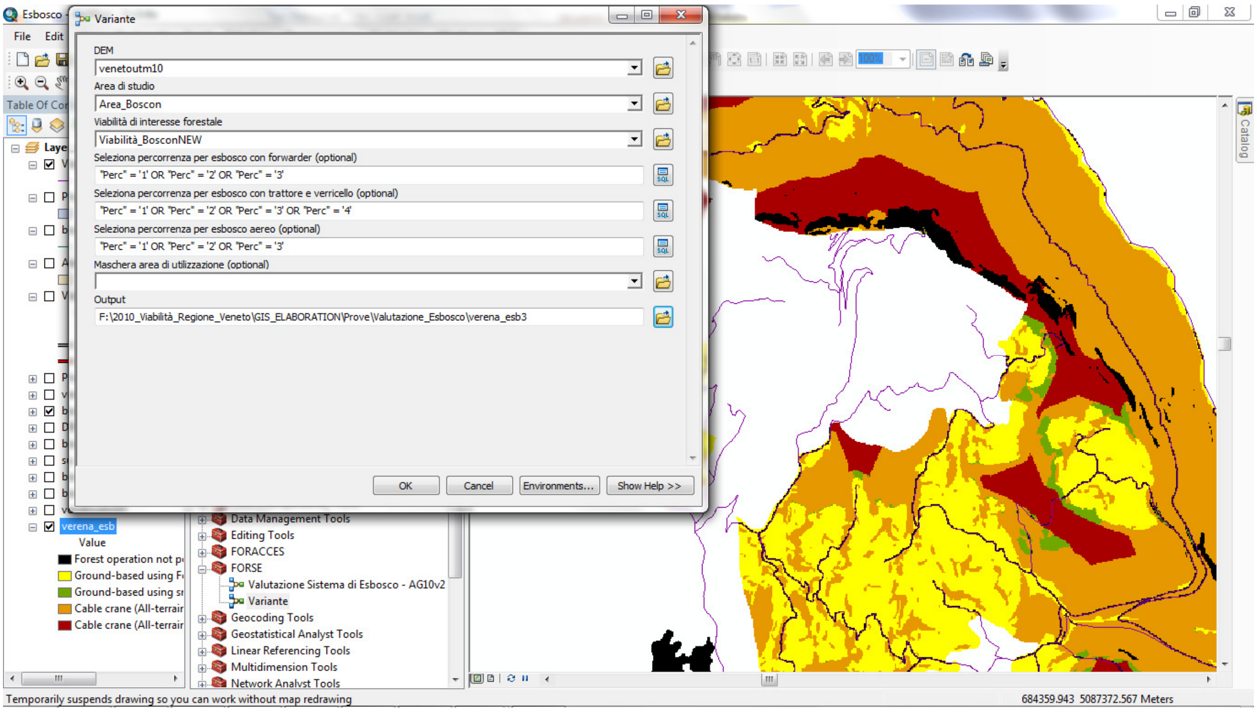


Figure 30 - Input mask of the model FORSE

3.3.3. Describing processes of the model

Firstly, the forest road network (first input data) are clipped (*clip tool*) using the administrative boundaries polygon (second input data). The same polygon feature is used to extract (*extract by mask tool*) the part of interest of the Digital Elevation Model (third input data).
The extracted forest road network passes through a selection procedure (*select by attributes*) that uses the operative classification data contained in the attribute table. The part of the road network having the required operative class will then be selected.
The extracted DEM is used to derive the slope map. From the slope map the part of surface within the defined ranges of slope for each system (first limit of feasibility of the systems) is extracted.

To calculate the extraction distances and the relative limit of the terrain condition have been used the tool *Path distance*. The Path Distance tool is a tool for cost distance analysis accounting for both horizontal and vertical cost factors as well as true surface distance. The vertical factors determine the difficulty of moving from one cell to another, while accounting for the vertical elements that may affect the movement (ESRI, 2011). In the model the vertical factor parameters have been set as values of terrain slope to distinguish the uphill and downhill extraction according to the relative limits.
The Path distance analysis is performed for each system of extraction. Each output map is then reclassified according to the feasibility of each system and the three output maps are then unified to create the final map representing of the extraction system.

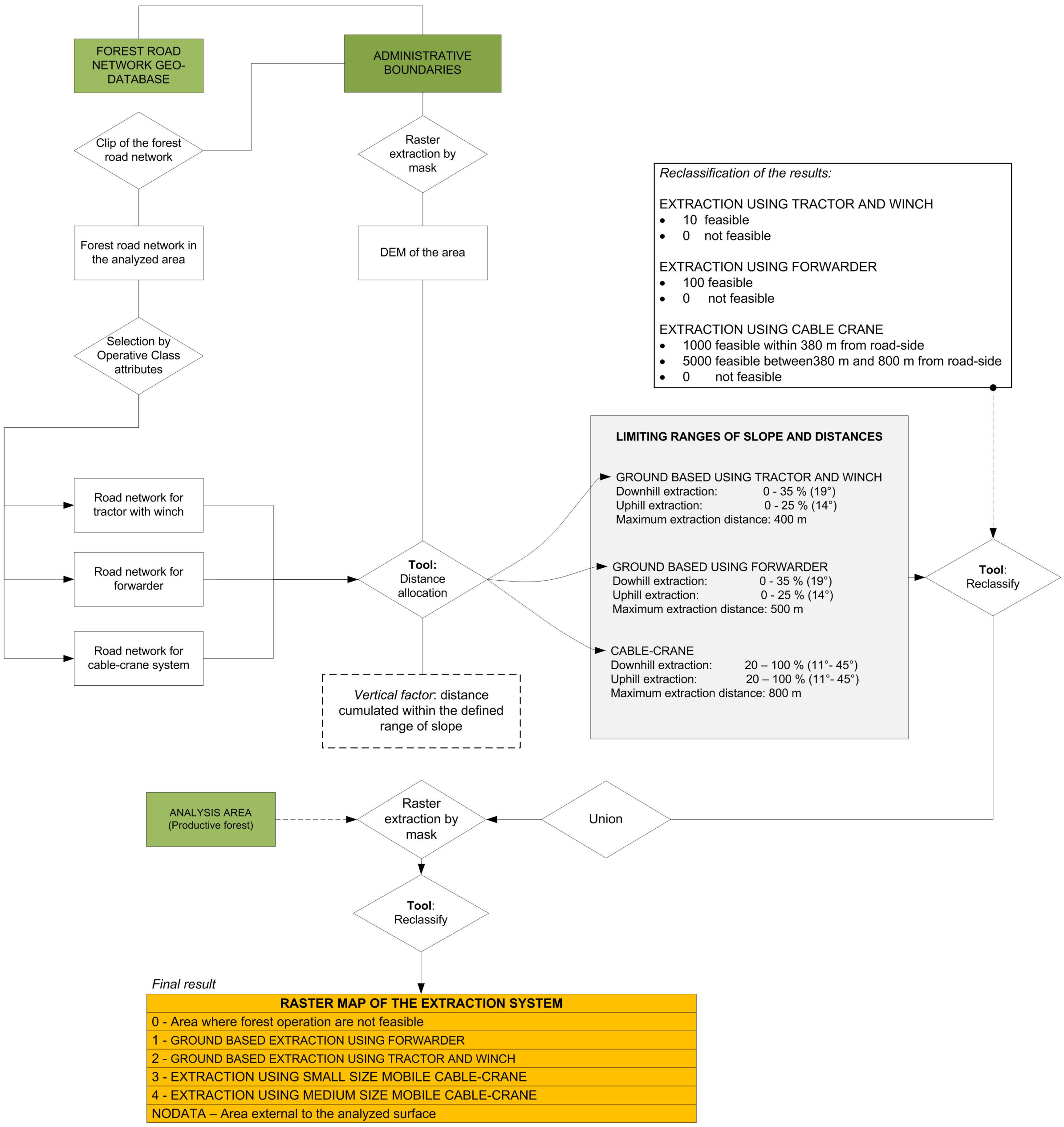


Figure 31 - Logical process of the model for the evaluation of the system of extraction (FORSE)

3.4. GIS-based tool to evaluate the gradient of roads (ROADGRAD)

3.4.1. Aim of the model

The third model (ROADGRAD) evaluates the vertical gradient of the forest roads based on the Digital Terrain Model (DTM). The resulting map contains the information about the slope of the roads that can be used to determine the presence of limiting point for the transit or to evaluate the needs of drainage structures.

3.4.2. Basics of the model

The vertical alignment (slope) of a forest road is one of the most important parameters that have to be evaluated in order to understand both the level of required maintenance and both the type of vehicles that can transit on the road.
Vertical alignment is often the limiting factor in road design for most forest roads. Frequently grades or tag lines are run at or near the maximum permissible grade. Maximum grades are determined by either vehicle configuration (design/critical vehicle characteristic) or erosive conditions such as soil or precipitation patterns. Depending on road surface type, a typical logging truck can negotiate different grades.
Table 18 reports the limiting values of slope gradient as reported by Hippoliti (1976).

Table 18 – Limit of slope gradient of forest road proposed from Hippoliti (1976)

Primary road	M.S. Opt	M.S. max	S max
	%	%	%
Primary for Truck	3-8	10	14
Secondary for Truck	3-8	12	18
Tractor road	3-8	14	25

Notes: M.S. Opt: optimal mean gradient (%); M.S. Max: maximum mean gradient (%); S max: maximum gradient (%)

These values have been considered in the model to understand the critical point in the forest road network.
It should be taken into consideration that today's loaded trucks are traction limited and not power limited. They can start on grades up to 25 % on dry, well maintained, unpaved roads and once in motion they can typically negotiate steeper grades (FAO, 1998).

The inputs of the processes are:

Forest roads (polylines features): the model asks to select the shapefile of the forest road network for which is intended to perform the analysis.

Digital Terrain Model: used to generate the contour line. High resolution data guarantee more precise results with higher elaboration-time.

Contour Line Interval: the definition of the range between the contour lines allows one to control the level of detail of the results. A good compromise seems to be an interval of 10 m for Digital Elevation Model with a resolution of 10 m or higher.

Critical slope: the definition of the values of critical slope is used to generate the point where the transit is limited for the vehicles. Two different values can be defined, considering the limits of two types of vehicles.

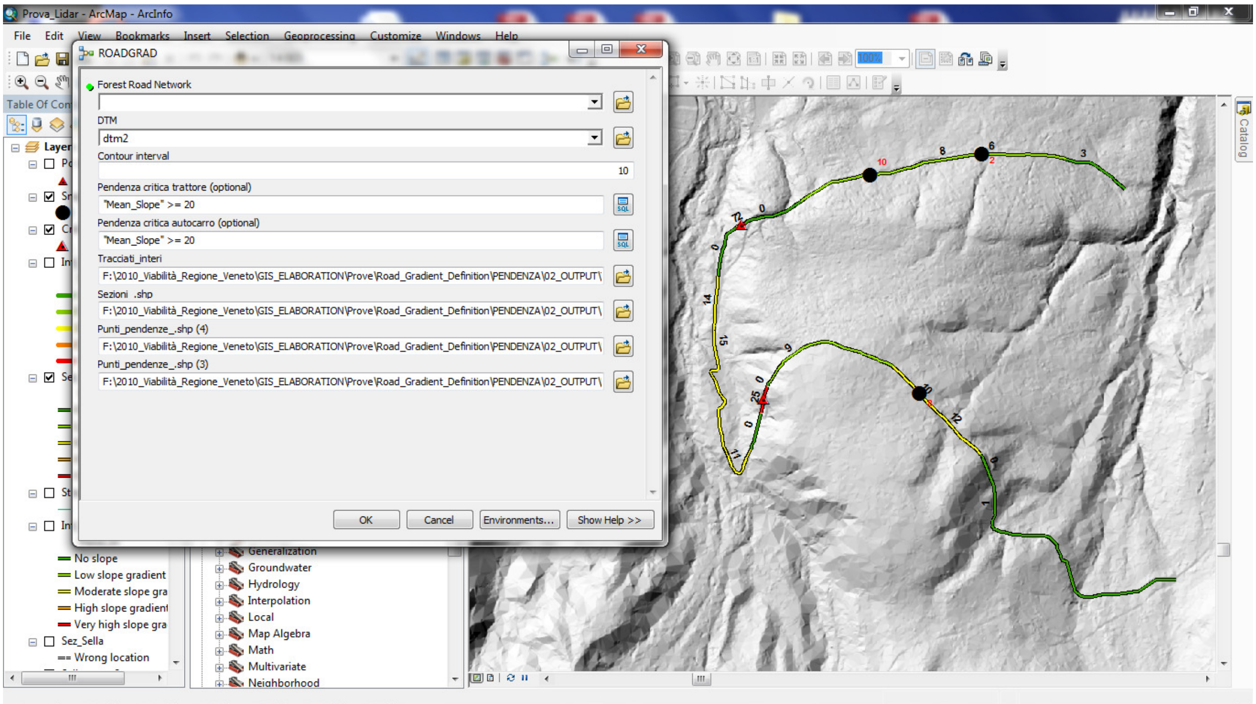


Figure 32 - Input mask of the model ROADGRAD

3.4.3. Describing processes of the model

Firstly, a buffer area along the forest roads (first input data) considered in the analysis is created. The resulting polygon feature is used to extract (*extract by mask* tool) the part of interest from the Digital Elevation Model (second input data). The extraction at this early stage of the small part of the DEM to be used in the analysis allows considerably reduction of the elaboration time. From the extracted DEM, the contour lines are created (*contour* tool). Contour intervals are defined as a parameter of the model. By modifying this value, the user can define the level of accuracy of the result. A multipoint features is then created in the intersection point between the roads and the contour lines (*intersect* tool). The resulting multipoint file is converted into a point features (*Multipart to singlepart* tool).
Using *dissolve* tool, the forest road network features included between two nodes are aggregated. The new forest road network polyline features are split in correspondence of the intersection point (*split line at point* tool).
The intersection points are then used to extract the elevation values from the DEM (*Extract values to point*).
New split forest road network polylines and the point features are then joined using *join field* tool and the value of the elevation of the point corresponding to the two vertexes of each section of roads are included in the attribute table.

From these values using the field calculator, the slope value of each section is calculated (first output of the model). Afterwards the section is re-aggregated (*dissolve tool*) to calculate the mean slope of each forest road (second output).
Finally, the defined critical slope values are used to select the sections of the forest road network where the slope can limit the transit of the vehicles. The selected sections are exported as point features (third output of the model).

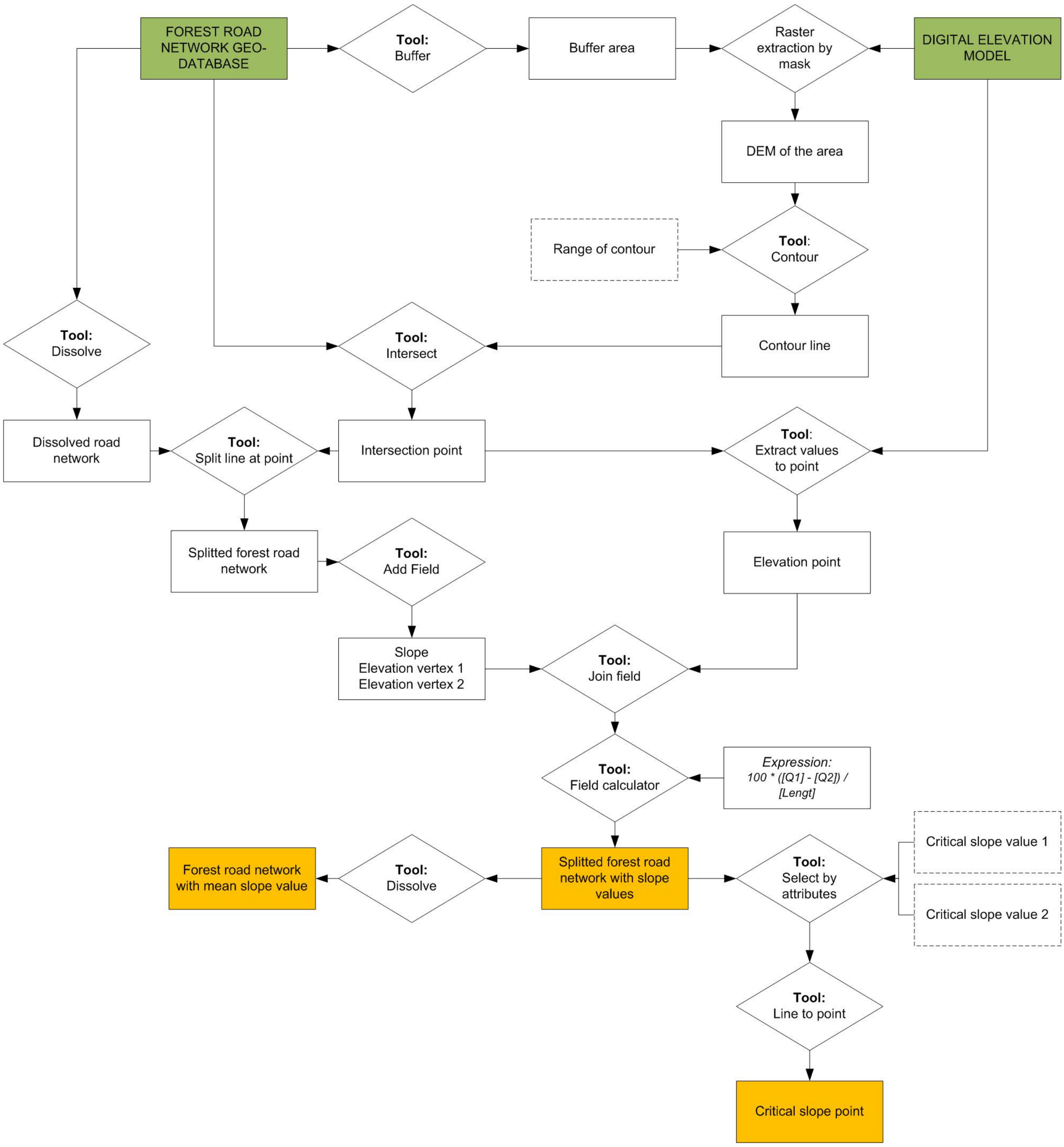


Figure 33 - Logical process of the model for the evaluation of the forest road slope (ROADGRAD)

3.5. Results

3.5.1. Evaluation of the accessibility of the territory

Once the model is run, FORACCESS produces as a result a thematic map representative of the accessibility of territory as represented in Figure 34.

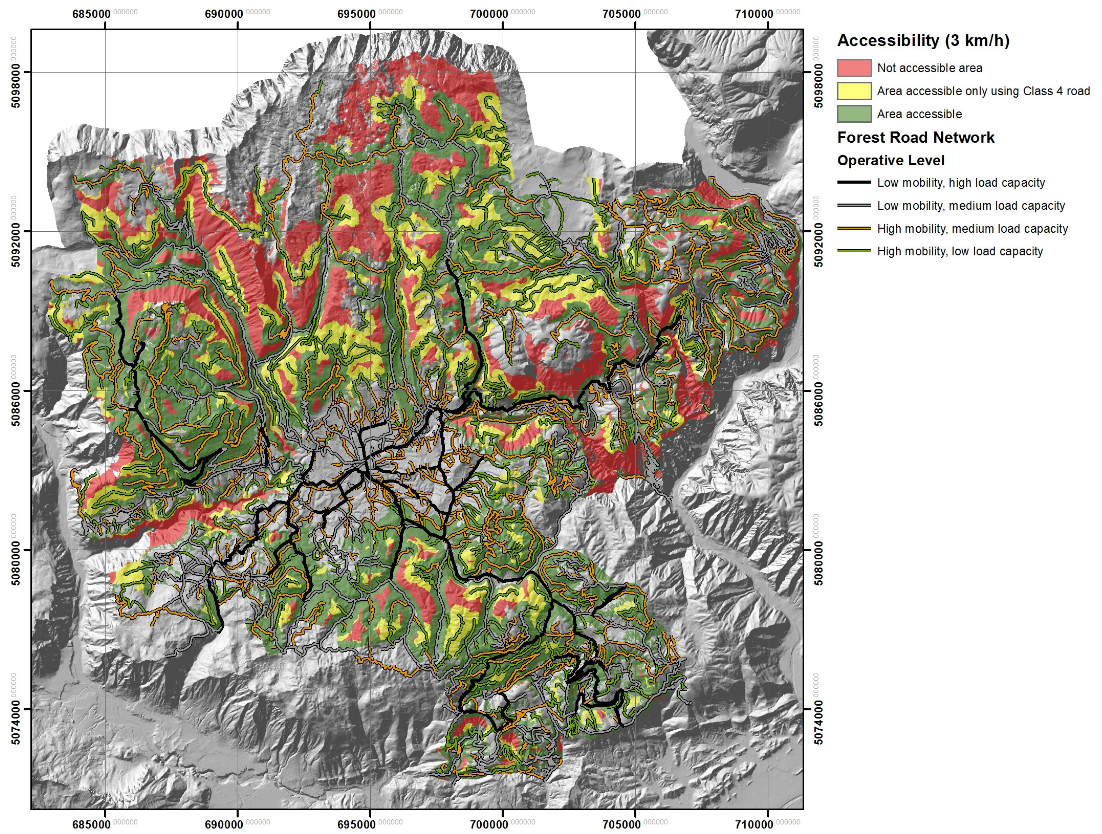


Figure 34 - Map of the accessibility for the territory of the Comunità Montana "Spettabile Reggenza dei 7 Comuni

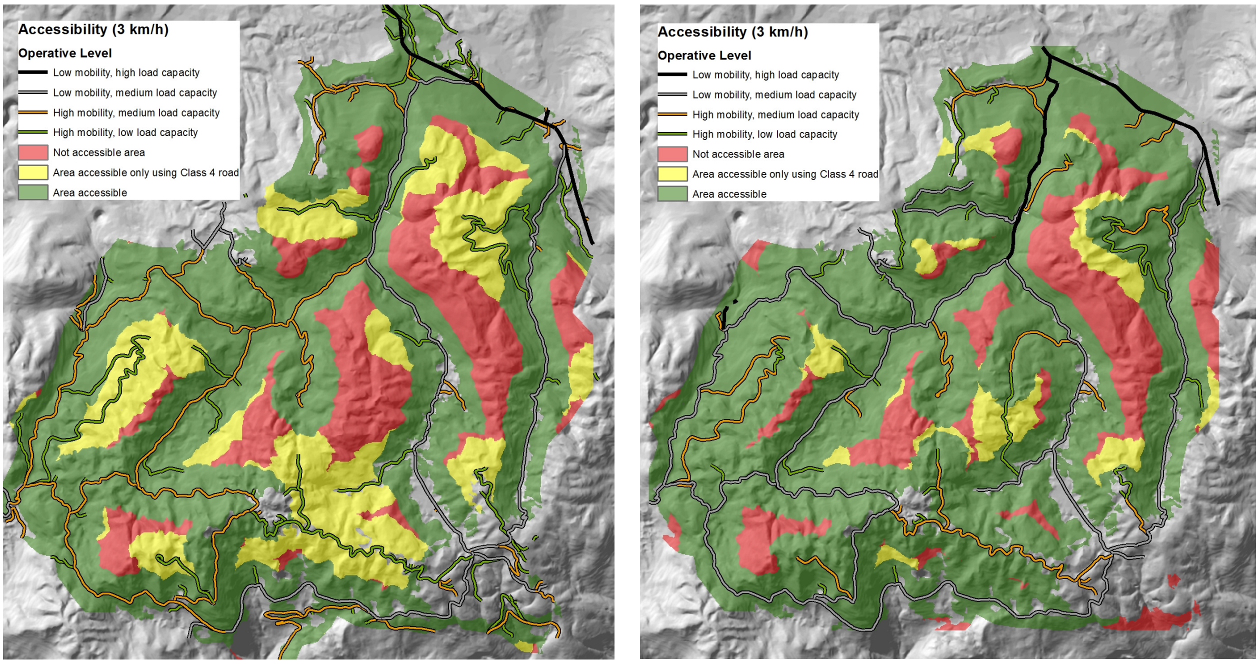
The analyzed area (as for example the forest surface) is divided in three classes. The green part is the fraction of the surface which is in actuality easily accessible using the present forest road network. In these areas the construction of new road are not necessary.

The yellow surface represents areas that are also accessible but in this case it is necessary for access to use roads with an operative Class 4. This means it is only possible to use small vehicles that often are not enough for the rational execution of the forest operations. In these areas, the construction of new roads is also not necessary but the possibility to upgrade the existing forest roads according to the management needs should be considered.

Finally, the red surfaces represent those areas not accessible from an operator within a walking time of 30 minutes (return time). In these surfaces the possibility to create a new road if the management strategies would require access to the area should be considered.

To ensure a result representative of the reality, it is required that the input data present sufficient accuracy.

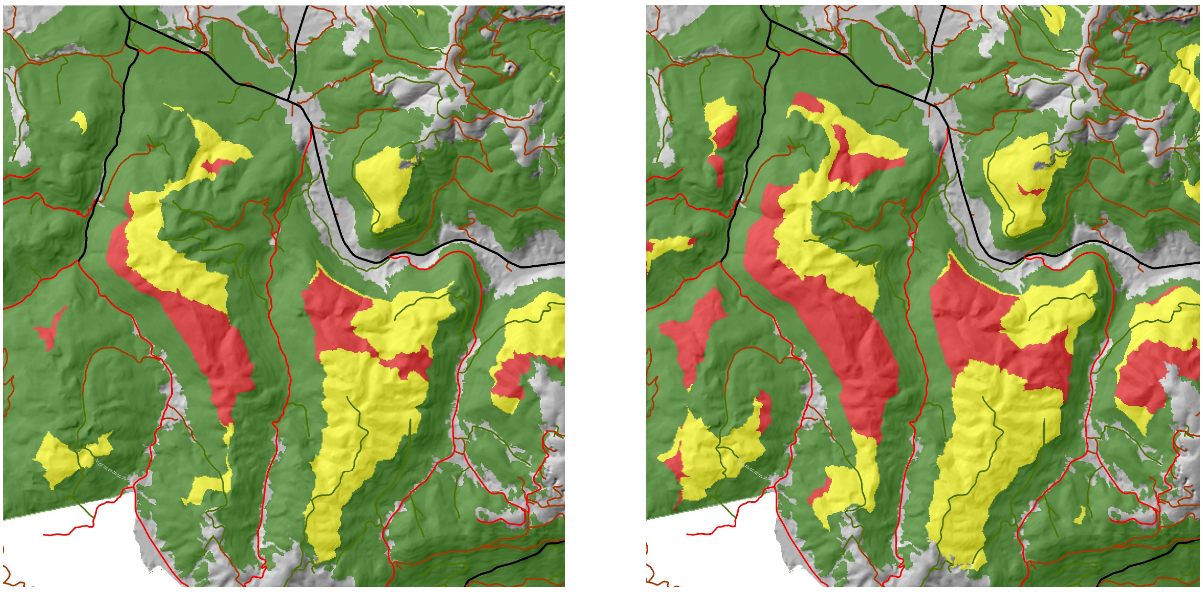
Figure 35 illustrates the output of the model using a forest road network before and after the survey in the field. In the second case, the information about the presence and the operative class of the road has been checked.



a) b)

Figure 35 - Output of the model FORACCESS using a forest road network before (a) and after (b) the field-survey

One can notice the difference between the two estimates. For this reason, especially where the evaluation is needed at a small scale, it is suggested to use road network data that has been checked and validated in the field. The model can be adjusted for different conditions by controlling the speed of the operator (Figure 36).



a) b)

Figure 36 - Output of the model considering different speed of the operator (3 km/h, a), (4 km/h, b)

A speed of 3 km / h for a slow operator and 4 km / h for a fast one seems to represent the reality. However, these values can be adapted to specific situations, allowing for example to adopt lower speeds in the case of increased roughness of the terrain.

The model for the evaluation of the accessibility of the territory has been applied to the entire Region. Following tables report the results in terms of accessibility of the forest as represented in the Regional Map of Forest Type (SB) for each Comunità Montana (Table 19) and for each Province (Table 20) considering two hypothetic operator speeds.

Table 19 - Level of accessibility of the forest for each Comunità Montana

Comunità Montana		SB	3 km h^{-1}			4 km h^{-1}		
		TOTAL	Accessible		Not accessible	Accessible		Non Accessible
		ha	%	% (*)	%	%	% (*)	%
BL	CM Agordina	38936	25	18	57	31	19	50
BL	CM Bellunese-Belluno-Ponte nelle Alpi	10170	55	10	35	61	9	30
BL	CM Cadore Longaronese Zoldano	23798	14	4	71	29	5	66
BL	CM Centro Cadore	39324	26	10	63	33	11	56
BL	CM Comelico-Sappada	21270	43	10	46	52	10	38
BL	CM dell'Alpago	9371	65	9	25	74	7	18
BL	CM della Valle del Boite	22351	40	10	50	48	10	42
BL	CM Feltrina	37337	49	8	43	57	7	35
BL	CM Val Belluna	20030	46	12	42	53	11	36
TV	CM del Grappa	6241	50	19	16	57	16	12
TV	CM delle Prealpi Trevigiane	21145	51	20	28	62	18	19
VI	CM Agno-Chiampo	12263	45	13	42	57	12	31
VI	CM Alto Astico e Posina	18547	32	13	55	39	14	47
VI	CM dall'Astico al Brenta	4557	69	8	22	81	6	12
VI	CM del Brenta	10061	48	7	46	55	6	39
VI	CM Leogra-Timonchio	10008	70	14	15	80	11	9
VI	CM Spettabile Reggenza dei 7 Comuni	30332	58	19	23	69	16	15
VR	CM del Baldo	14460	40	11	44	47	10	37
VR	CM della Lessinia	24556	54	14	23	64	11	16

* surface accessible only using roads with operative Class 4 where is to evaluate the possibility to improve the roads

Table 20 - Level of accessibility of the forest within for each Province and for the Region

Province	SB	3 km h^{-1}			4 km h^{-1}		
	TOTAL	Accessible		Not Accessible	Accessible		Not Accessible
	ha	%	% (*)	%	%	% (*)	%
Belluno	222587	36	11	52	44	11	45
Treviso	27386	51	20	25	61	17	17
Vicenza	85768	51	14	34	61	13	26
Verona	39016	49	13	30	58	11	24
Montainous area of Veneto Region	374757	42	12	44	51	12	36

* surface accessible only using roads with operative Class 4 where is to evaluate the possibility to improve the roads

3.5.2. Evaluation of the extraction system

Once run, the model FORSE produces as a result a thematic map representative of the system of extraction as shown in Figure 37.

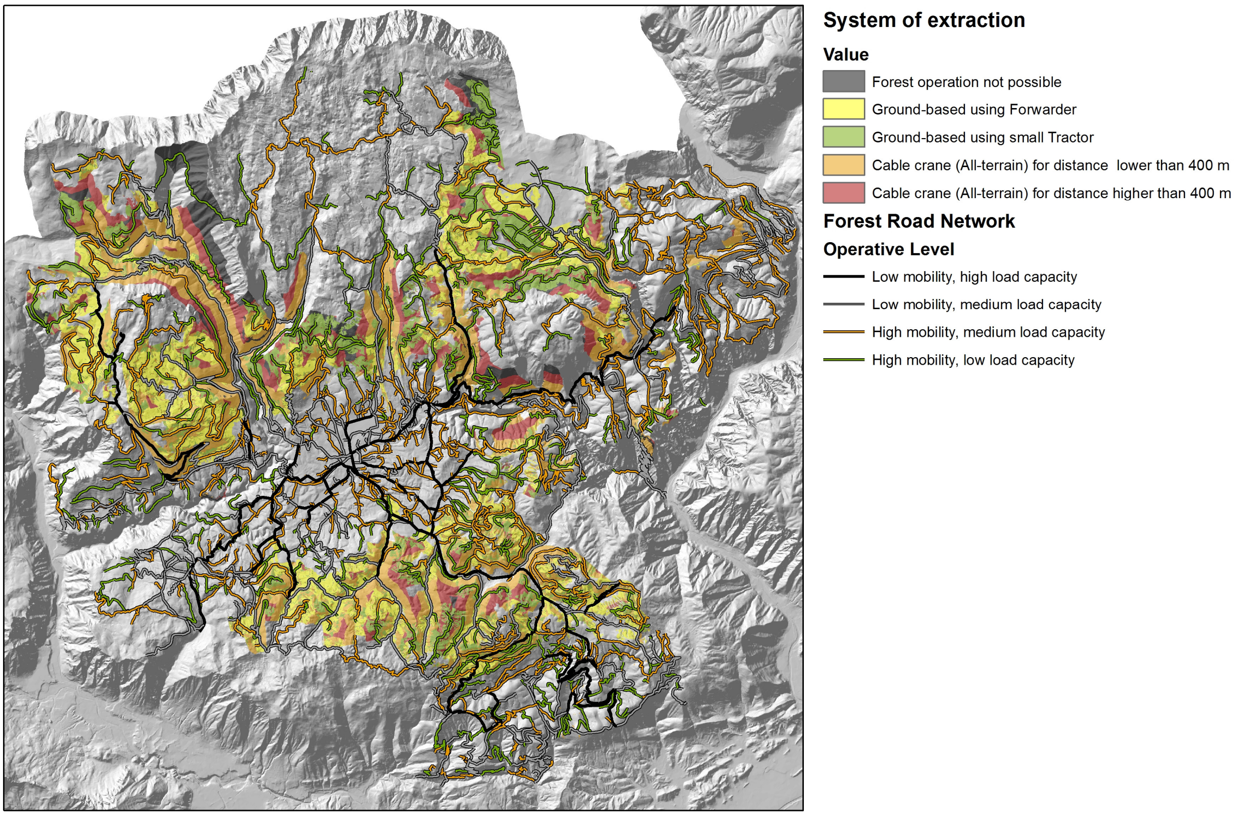


Figure 37 - Map of the feasibility of the extraction systems for the productive forests of the Comunità Montana "Spettabile Reggenza dei 7 Comuni"

The analyzed area (as for example the productive forest surface) is divided in four classes. The black area is the fraction of the surface in which forest operation are not feasible.

The yellow surface represents areas where the conditions allow using the forwarder to perform off-road transportation. This means that the present road allows the machine to access the area and the condition of the terrain is gentle.

The green surface represents those areas where the extraction can be done using a tractor with winch.

Finally, orange and red surfaces represent the areas where the extraction can be done only using cable crane systems. These areas are mainly located in steep terrain. The condition for the application of these systems is the possibility to access the area with the cable crane system. Different colors indicate the maximum length of the line, 400 m for a small size mobile cable system (orange) and 800 m for a medium size mobile cable system (red).

Also in this case to ensure a result representative of the reality, it is required that the input data present a sufficient accuracy, especially for what concerns the operative class of the roads.

Figure 35 illustrates the output of the model using a forest road network before and after the survey in the field. In the second case, the information about the presence and the operative class of the road has been checked.

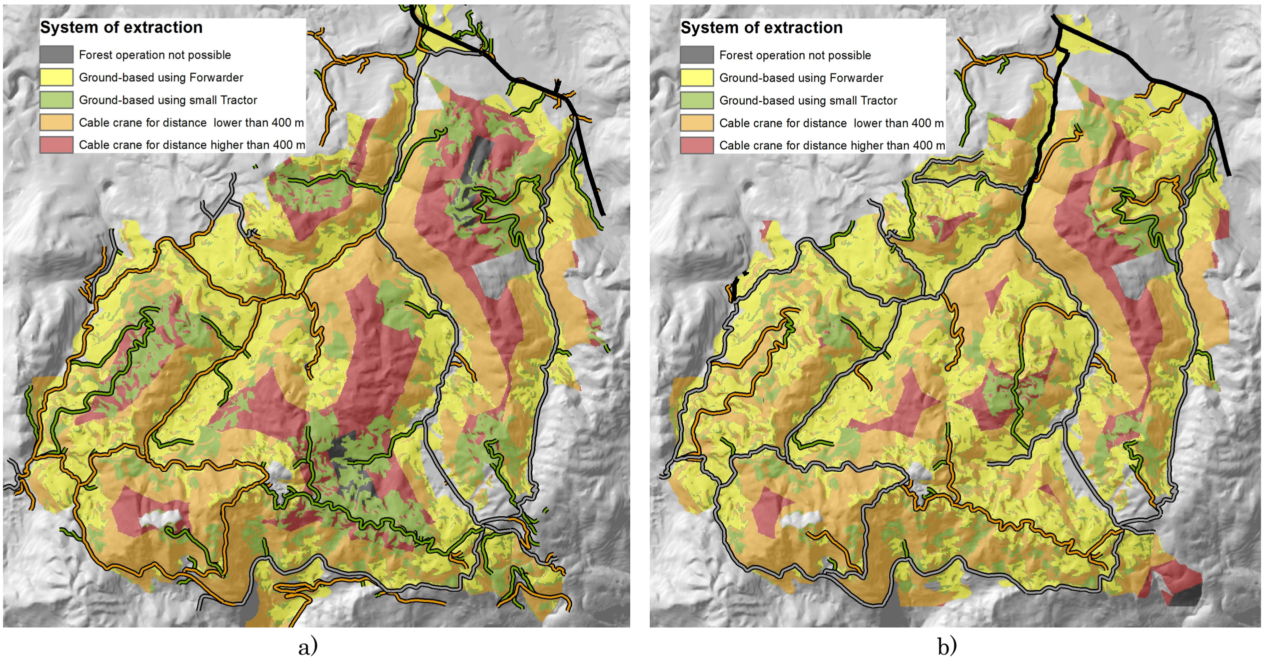


Figure 38 - Example of an output of the model FORSE using a forest road network before (a) and after (b) the survey in the field

The correspondence of the results with the reality have been controlled in the field by analyzing a number (19) of forest operations already performed inside the area and the utilized extraction methods and, in most of the cases (12), the indications of the model were right.

It has been highlighted that the greater cause of wrong evaluations is due to elements that are not included in the model, especially the roughness of the terrain. Due to the terrain roughness, in areas indicated from the model as adapted to the use of the Forwarder, in reality it cable crane systems should be used.

Despite this the model has proven to be a valid tool for the evaluation of the areas where forest operations are feasible and the extraction system more appropriate. These indications can be used to evaluate the benefit of the construction or the improving of forest roads.

For example in areas indicated as suitable for the use of tractor and winch the possibility to improve the forest road to access the area with a larger machine type, such as forwarders, can be evaluated.

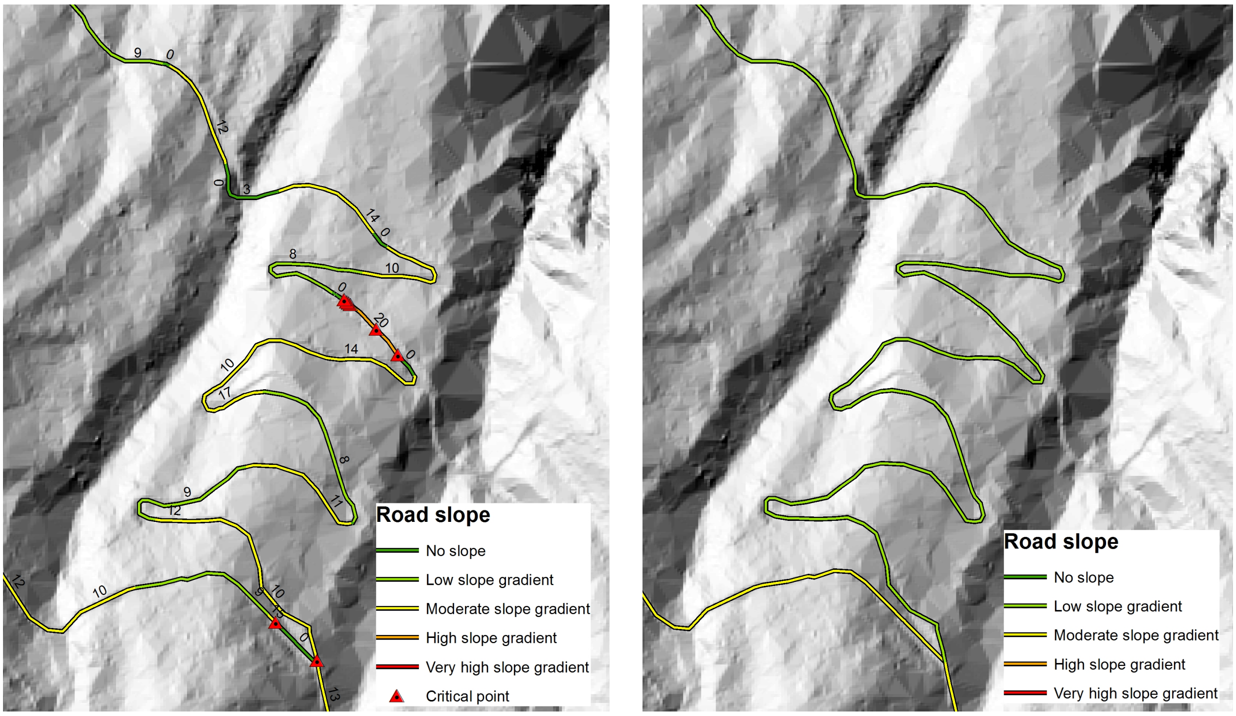
The model is intended for a medium-large scale of application, in which the results should be interpreted and fit to the situation of the analyzed area.

For more operative purposes and more local evaluations, additional factors should be added to the analysis. In particular, the evaluation of the terrain roughness that heavily affects the feasibility of the ground-based extraction system seems important and must be evaluated in the field.

Moreover the efficiency of application of a particular extraction system does not depend exclusively on the characteristics of the terrain, but is also influenced by the characteristics of the forest stands (government, density and structure) and the type of cut.

3.5.3. Evaluation of the road gradient

Once run, the model ROADGRAD produces 3 layers as results (Figure 39). The first layer (polylines) reports the slope gradient of the forest road network sections split in correspondence of the intersection with the contour lines. The second layer (polylines) reports the mean slope gradient calculated for each complete road. The third layer (points) includes the points critical for the transit. Setting different critical slope values are possible for example to evaluate the limiting point for different types of machines.



a) b)

Figure 39 - Examples of the output of the model ROADGRAD, slope values for road sections (a) and mean slope value for each road

The correspondence of the results with the reality has been controlled through measuring a number of forest road slope values (132) directly on the field using a Vertex Laser system.
The validation shows that the model correctly estimates the slope value (with an error lower than 3 percentage degrees of slope) in 70 % of the cases.
The evaluation of the reliability of the results highlights that the cause of errors mainly concerns the quality of the input data.
In particular 3 main causes of error have been identified, the wrong location of the road on the terrain (Figure 40), the inaccuracy of the digital elevation model and the wrong location of the points of survey.
The model has been tested using Digital Elevation Model with different resolutions and the precision of the results increase at the increasing of the resolution of the DEM. For what concerns the definition of the contour line intervals, a good compromise seems to be an interval of 10 m for Digital Elevation Model with a resolution of 10 m or higher, while using DEM with lower resolution it is suggested to avoid the use of contour intervals lower than the resolution.

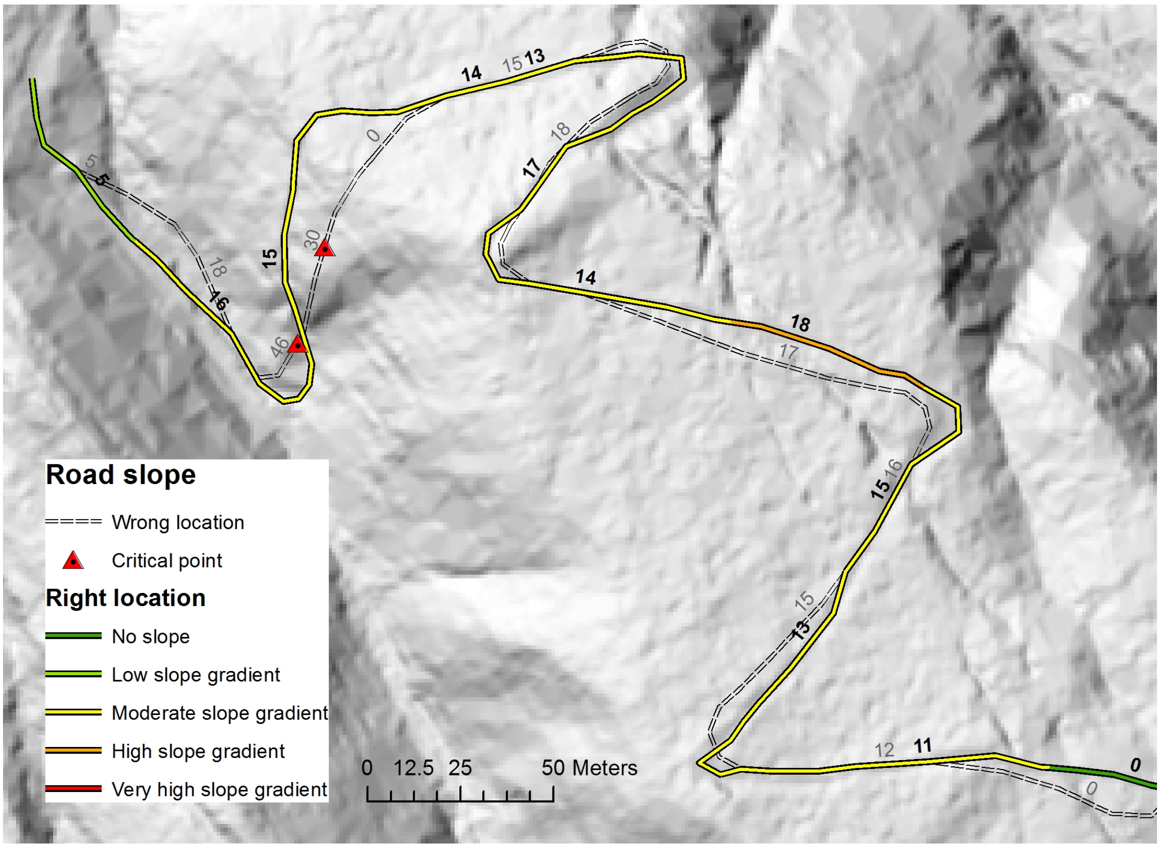


Figure 40 - Error due to the wrong location of the road on the terrain

The model has proven to be a valuable tool for the evaluation of the road gradients and the points where the slope became a limiting factor for the transit of the machine operating in the forest.
The precise knowledge of the slope of each road section is also useful to define the priorities in the planning of the maintenance interventions. In fact the gradient, or slope, of a road segment influences the erosion rate. Water flows more quickly down steeper road segments, resulting in greater erosive power (higher shear stress) (Luce and Black 1999a). For this reason, sections with a greater slope are more susceptible to erosion and require more attention both during the construction (with adequate drainage structure) both in the planning of routine maintenance.

3.6. Conclusion

The three models utilize the data contained in the geo-database of the forest roads as a basis for the elaboration of thematic maps to support its management.
The application of the models make possible to evolve from the simple informative level to an operative one through the integration of the forest road network with other elements of the territory understanding its needs.
The first model (FORACCESS) evaluates the accessibility of the territory. From the result, an initial interpretation of the level of accessibility of the area considering the time of access by an operator is possible. The output can be used as a first indication of the need for the construction of new road by comparing the spatial distribution of the inaccessible areas and the need of accessibility (given for example, from the characteristic of the forest and its silvicultural needs).
The necessity for the construction of new roads has also been evaluated as another important aspect, related to the technical feasibility of forest operation. For this purpose the second model (FORSE) which evaluates the feasible area for each wood extraction system has been developed.
In fact while the forest road network allows access to the forest area, the system of extraction can be considered as the limit which defines the part of forest that can be managed with the present roads.
The third model (ROADGRAD) has been developed to support the management of the existing forest road network determining the vertical gradient of the forest roads. The resulting map contains the information about the slope of the roads that can be used to determine the presence of the limiting point for the transit or to evaluate the needs of drainage structures. The precise knowledge of the slope of each road section is also a useful information to define the priorities in the planning of the routine maintenance interventions.
For a complete evaluation of the management strategies more factors should be considered. The resulting task is complex because of the many aspects involved in forest road management including the natural environment and the socio-economic context in which the road network is located. For that reason, the management of forest road networks needs methods to integrate multiple objectives and set priorities across those different goals.

Chapter 4. Spatial Multi-Criteria Decision Process to define maintenance priorities and management opportunities of primary forest road network – an Alpine case study"

4.1. Introduction

4.1.1. Management and maintenance of the forest road network

Routine road maintenance is vital to keep a road system serviceable and to maintain the proper working of its drainage system. A well-maintained road can be protected from rapid deterioration, minimizing sediment production (Dubè et al., 2004), and reducing trucking costs (Brown, 2000).
Each year, a consistent amount of money is spent to upgrade and maintain forest road networks. In order to optimize the use of limited funds, it is of primary importance to set investment priorities while meeting management and environmental goals.
The resulting task is complex because of the many aspects involved in forest road management including the natural environment and the socio-economic context in which the road network is located.
For that reason, the management of forest road networks needs methods to integrate multiple objectives and set priorities across those different goals. Additionally, the management of forest roads involves a mixture of environmental data and models with expert judgments on social aspects.
Managers generally focus on single problem in order to better understand the conditions of the road network and to set maintenance and upgrade priorities. The Washington Department of Natural Resources and Boise Corporation, for example, have created an empirically based model (SEDMODL), used to estimate road-related sediment production and transport to streams (Dubè et al., 2004).
Potocnik et al. (2006) investigate a traffic management strategy in the preserved forest area of the Pokljuka highland (Slovenia) considering the touristic importance of the roads.
Spatial Multi Criteria Decision techniques provide tools for aggregating the geographical data and the decision-makers preferences into unidimensional value or utility of alternative decisions combining a set of criteria to achieve a single composite basis for a decision according to a specific objective (Eastman et al., 1993).
Although a variety of techniques exist for the development weighting the criteria, one of the most promising would appear to be that of pairwise comparisons developed by Saaty (1980) in the context of a decision making process known as the Analytical Hierarchy Process (AHP). In the pairwise comparison method, the decision-maker is asked to give the relative importance to the criteria by comparing them two by two. Schmoldt et al. (2001) describes the basis of the application of the Analytic Hierarchy Process in Natural Resource and Environmental Decision Making.
The Analytic Hierarchy Process appears to have the potential for managing existing road systems where research has not yet uncovered quantifiable relationships between cause and effect, meaning that the synthesis of road inventory data to set investment priorities should depend in part on professional judgment. According to this idea, Coulter et al. (2006) developed maintenance priority definition methodologies that use AHP analysis in order to minimize the environmental impact to soil and water resources from forest roads.
Shiba (1995) used an AHP-based approach to identify the benefit structure of road network system and to improve the development strategy in mountainous areas while considering complex socio-economic problems.

AHP analysis and GIS tools have been recently applied to evaluate the needs of forest roads in a mountainous area (Cavalli et al. 2010) and to evaluate new forest road location alternatives (Abdi et al. 2010).
The present study uses the combination of GIS tools and AHP techniques to define the maintenance priorities and the management opportunities of primary forest road network in an Alpine area of Italy.

4.1.2. Principles of Analytic Hierarchy Process Method

Analytic Hierarchy Process (AHP), since its invention, has been one of the most widely used multiple criteria decision-making tools at the hands of decision makers and researchers (Omkarprasad S.V. et al. 2006).
AHP method, developed by Saaty (1980) is based on the following three principles: decomposition, comparative judgment and synthesis of priorities.
The first step in the AHP procedure is to decompose the decision problem into a hierarchy that represents the decision problem starting from the final goal to the attributes level. The alternatives are represented in GIS databases where each layer contains the attribute values assigned to the alternatives, and each alternative (cell or polygon) is related to the higher-level elements (attributes). Typically, the hierarchical structure consists of four levels: goal, objectives, attributes and alternatives (Figure 41). This structure links the AHP method to GIS-based procedures.

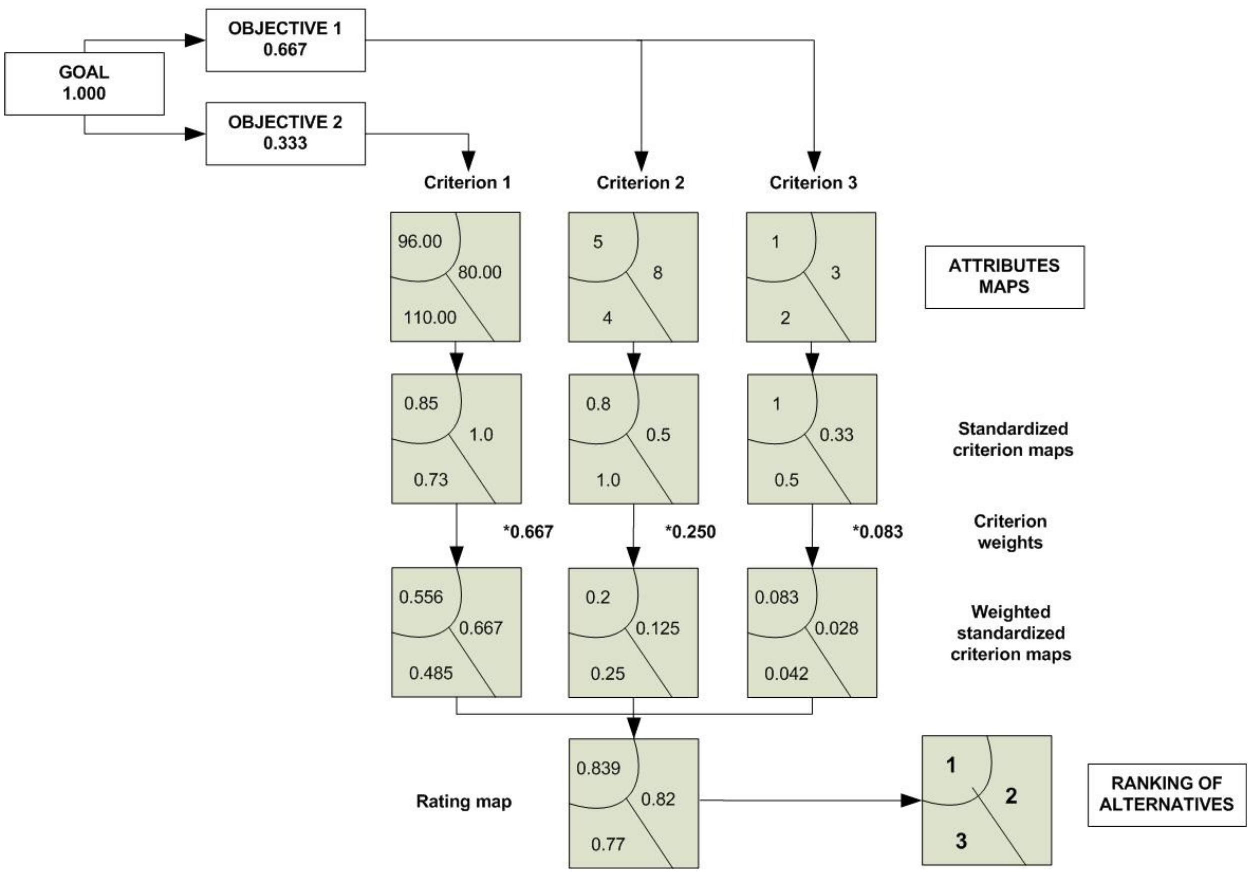


Figure 41 – Analytic hierarchy process (AHP) procedure and GIS-based rating of alternatives

After the definition of the hierarchy structure, the decision elements have to be compared on a pairwise basis. A pairwise comparison is the basic measurement mode employed in the AHP procedure. In this way the complexity of the decision making process is strongly simplified since only two components are considered at any given time.
The comparison follows three steps. Firstly, a comparison matrix is developed at each level of the hierarchy.
The method employs an underlying scale with values from 1 to 9 to rate the relative preferences for each pair of criteria (Table 21).

Table 21 – Scale for pairwise comparison

Intensity of importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extreme strong importance
9	Extreme importance

After the completion of the *matrix of pairwise comparison*, we can start to compute the criterion weights for each level of the hierarchy. This step involves the following operations: sum the values in each column of the pairwise comparison matrix, and divide each value by its column total (*normalized pairwise comparison matrix*) and finally computing the average of the elements in each row.
The following operation is to aggregate the relative weights of the levels obtained in the second step to produce composite weights. This is done by means of a sequence of multiplications to the matrices of relative weights at each level of the hierarchy. The sequence is one in which the relative weights matrix for the second level is multiplied for the relative weights matrix for the third level, and then this resulting matrix is multiplied by the relative weights matrix for the next lower-level.
This process is continued until all levels from the second level to the bottom level have been multiplied together forming a vector of composite weights.
To determine if the comparisons are consistent, the estimation of the consistency ratio (CR) is used. CR is a single numerical index and it is defined as the ratio of the consistency index CI to an average consistency index RI:

$$CR = \frac{CI}{RI}$$

Following the illustrations of Saaty (1977), who calculated RI values up to a matrix order of 15, matrices with an order greater than 8 have an RI order of magnitude value of about 1.45 (Table 22).

Table 22 – Value of the RI for different order of the matrix

N	2	3	4	5	6	7	8
RI	0.00	0.52	0.90	1.12	1.24	1.32	1.41

The consistency index CI can be directly calculated from the preference matrix:

$$CI = (y_{max} - n)\frac{1}{n-1}$$

Where y_{max} is the greatest eigenvalue of preference matrix and n is the order of the matrix.
The pairwise comparison can be considered consistent if CR < 0.10.
If CR > 0.10, the original pairwise comparison matrixes have to be revised and the procedure repeated.
The pairwise comparison procedure can be employed only for a relatively small number of elements at each level of the decision hierarchy. Therefore, it can only be applied to problem involving a relatively small number of alternatives. When a large number of alternatives are considered, the AHP procedure is terminated at the attribute level, and the attribute weights are assigned to the attribute map layers and processed in the GIS environment.

4.2. Aims of the study

Define a methodology to:

1 Rank the maintenance priority according to the actual condition and the actual needs of a forest road network;
2 Define the optimal management strategies that meet the accessibility needs of the territory.

4.3. Material and methods

4.3.1. Study area

The study area is within "Altopiano dei Sette Comuni" in the North-Eastern part of Italy (latitude (N) of 45.56 – 45.52 longitude (E) of 11.23 – 11.28). The region is mainly occupied by Norway Spruce (*Picea abies*) and Beech (*Fagus sylvatica*) forests.
This area represents a meaningful case study because the forest road network within this area is varied and involves many different preeminent functions.
The recreational function is primarily a result of the presence of many historical sites related to the First World War and scenic hiking trails in the area. The silvicultural function is also important as expected with the presence of productive forest. Finally, the forest road network has to guarantee access for the farming activities.
The primary forest road network extension inside the area is 107.8 km, with a density of 26 m/ha. The extension of gravel roads is 80 km. 68.1 km (65.4 %) of the network is accessible without restrictions (public roads) while 39.7 km (34.6 %) present restrictions.

4.3.2. Layout of the analysis and problem definition

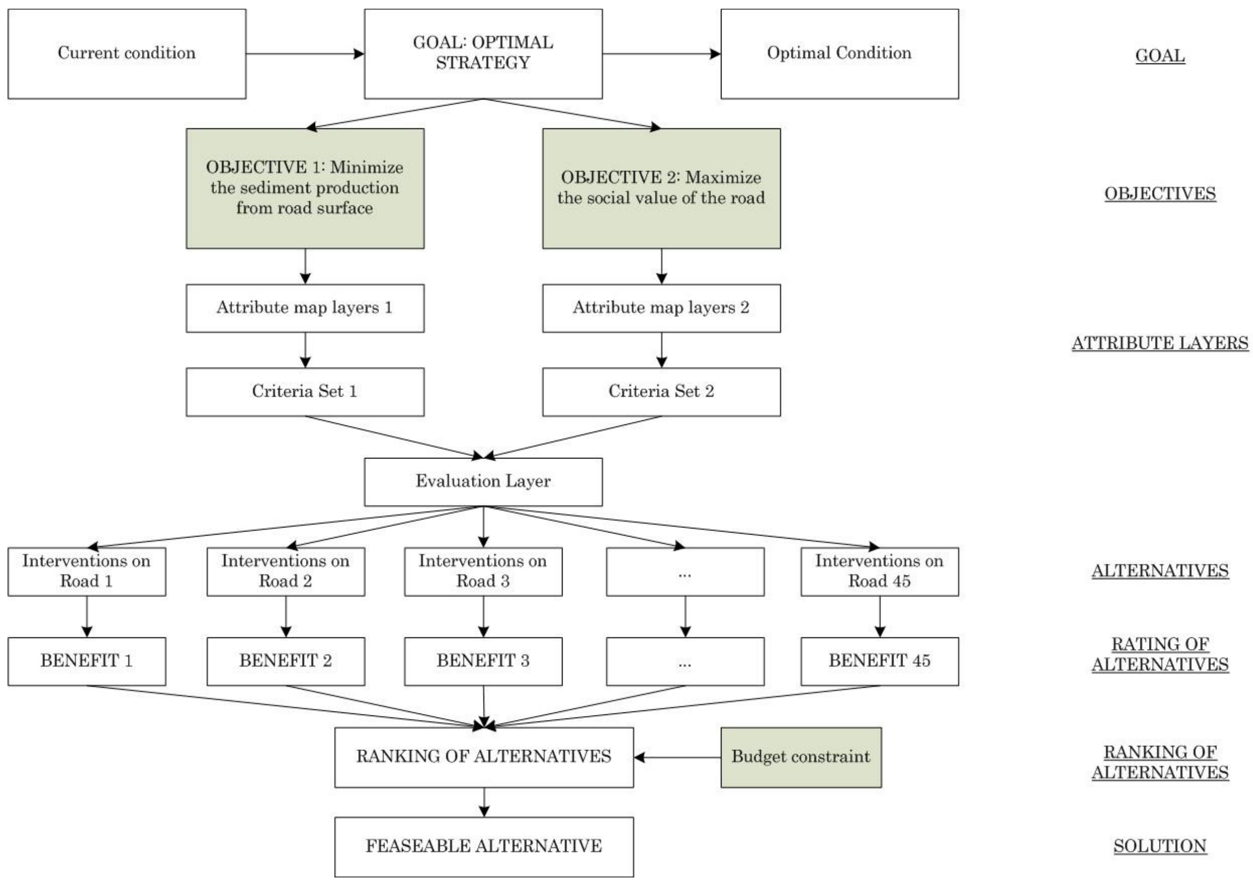


Figure 42 – General layout of the AHP analysis

Any decision-making process begins with recognition of the decision problems. A spatial decision problem is the difference between the desired and the existing state of a real-world geographical system.

In this context, a decision is needed when a problem or an opportunity exists, when something is not as it should be or when something can be improved. Simon (1960) suggests that any decision-making process can be structured in three major phases: *intelligence* (is there a problem or an opportunity for change?), *design* (what are the alternatives?), *choice* (which alternative is best?) (Figure 42).

One of the most problematic issues inside the study area is the maintenance of the forest road network. In particular, the management strategy requires a method to support the decision to use the economic resources for road network maintenance. The goal of the analysis is this perspective to find the optimal maintenance strategy.

The procedure passes through the evaluation of the actual condition and the actual maintenance strategies to search for the elements to improve. The study over this territory highlights the production of sediment from the gravel road surfaces representing the most frequent and dangerous process directly connected with the presence and the maintenance of the forest road network. The minimization of this process has been considered as the first objective.

The other leading elements in determining maintenance interventions are the type and level of use of the forest road. Following a multi-functional approach, the maximization of the social values have been considered as second objectives in the priorities definition.
The set of criterion and the hierarchical structure of the decision problem have been developed through the examination of the relevant literature regarding the analyzed aspect and through expert and stakeholders opinion.

4.3.3. Criteria evaluation

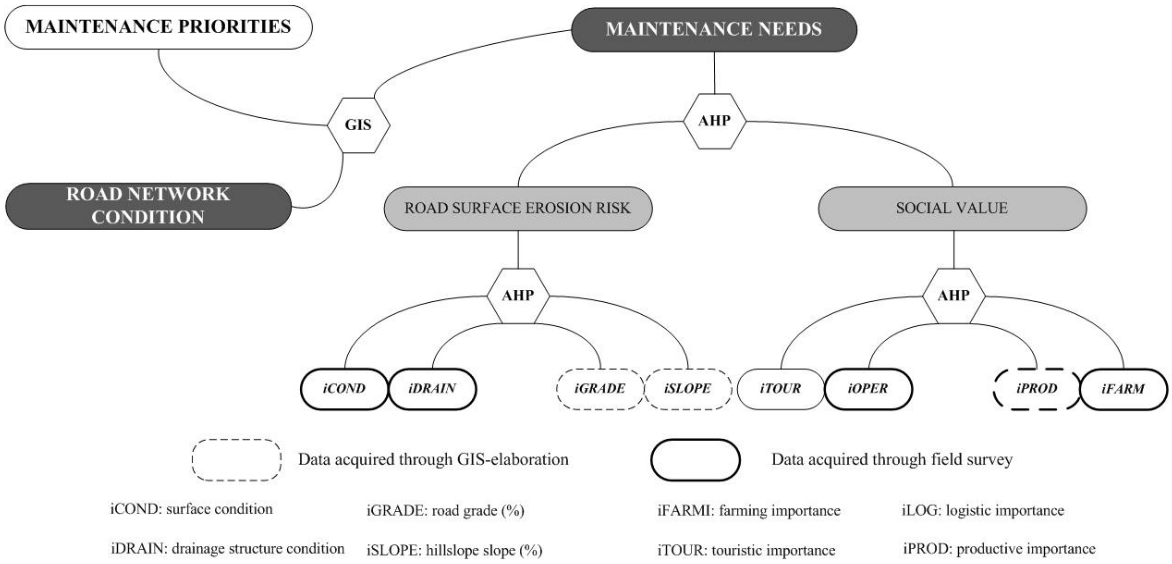


Figure 43 – Structure of the analysis and integration with GIS

Minimization of the risk of sediment production from forest road surface (Objective 1): Sediment can be eroded from all road features but road surface erosion is generally the dominant source of sediment (Ramos-Scharron and MacDonald, 2007b).
A recent review paper on surface erosion and sediment delivery model for unsealed road (Fu et al, 2010) effectively describes the main factors highlighted in literature.
The factors affecting surface erosion from road include rainfall intensity and duration, snowfall, the characteristic of surface materials, the characteristic of the road surface, road slope, traffic, construction and maintenance and the contributing road area (MacDonald and Coe, 2008). The gradient, or slope, of a road segment influences the erosion rate. Water flows more quickly down steeper road segments, resulting in greater erosive power (higher shear stress) (Packer 1967; Swift 1984; Vincent 1985; Bilby et al. 1989; Elliot and Tysdal 1999; Luce and Black 1999a).
The width of the road and the amount of traffic on a road both influence the amount of surface erosion produced from the road tread. Research by Reid (1981), Reid and Dunne (1984), Grayson et al., (1993), Luce and Black, (1999b), Ramos-Scharro´n and MacDonald (2005), Sheridan and Noske, (2007), Ziegler et al., (2001a) was specifically aimed at determining the effects of traffic on road erosion. All studies showed increasing erosion rates with increased traffic use.
According to the literature, the set of criteria considered for Objective 1 are: road slope, surface condition, presence of drainage structure, level of traffic and hillslope slope (Table 23).

Maximization of the social value of the road network (Objective 2): to evaluate the social value, the different functions that each road can perform have been considered. The definitions of the functions have been discussed with stakeholders inside the studied area.
In particular, the following have been considered: touristic importance (access to important tourist sites), farming importance (access to farming activities) and operative class (actual constructive parameters of the road and ease of transit) (Table 23).

Table 23 – Considered criteria and relative evaluation methods

Criteria	Evaluation Methods
Objective 1 – Erosion risk	
Road gradient (*i*GRADE)	GIS analysis (Model based on contour line)
Surface condition (*i*COND)	Visual evaluation (field survey)
Drainage system (*i*DRAIN)	Visual evaluation (field survey)
Traffic (*i*TRAFFIC)	GIS analysis (based on Network analysis)
Location of the road (*i*SLOPE)	GIS analysis (based on Digital Terrain Model)
Objective 2 – Social value	
Touristic importance (*i*TOUR)	GIS analysis (access to touristic sites)
Operative class (*i*OPER)	Visual evaluation (field survey)
Farming importance (*i*FARM)	GIS analysis (access to agricultural/farming sites)
Productive importance (*i*PROD)	GIS analysis

Once the hierarchical structure of objectives and attributes has been established (Figure 43), each criterion can be represented as a raster map layer in the GIS database.
Information about surface condition, presence of drainage structures, operative class, touristic and farming importance has been collected during the field surveys and reported as attributes to the layer representing the forest road network. To determine slope gradient, hillslope slope and level of traffic in a representative layer, three semi-automated analysis procedures have been developed using Digital Terrain Model (DTM) and Forest Type Regional Map as input.
Multi-criteria decision analysis requires that the values contained in the various criterion map layers be transformable to comparable units. This is because if we want to combine the various criterion map layers, the scales must be commensurate.
Linear scale transformation is the most frequently used deterministic method for transforming input data into commensurate criterion maps. The linear scale transformation methods convert the raw data into standardized criterion scores (Voogd, 1983; Massam, 1988).
All of the data have been converted into standardized values using the *maximum score* (1) procedures.

$$x'_{ij} = \frac{x_{ij}}{x_{max}}$$

Where x'_{ij} is the standardized score for the *i*th object (alternative) and the *j*th attribute and x_{ij} is the raw score and x_{max} is the maximum score for the *j*th attribute. The scale of standardized scores range from 0 to 1000 where higher overall score values indicate greater benefit.
A pairwise comparison matrix was completed according to expert judgment and opinions of different people representing local perceptions regarding the importance of the different criteria.

AHP analysis was supported by the use of a specific application (AHP 1.1 - Decision support tools for ArcGIS) for multi-criteria analysis based on pairwise comparison (Marinoni, 2004a; Marinoni, 2004b).

4.3.4. Alternatives and constraint identification

The basis for the development of a road maintenance plan is a thorough understanding of the road system, its characteristics, and its needs. This is accomplished by establishing and maintaining an intensive inventory of the road system. The inventory has to provide the information necessary for identifying and prioritizing required maintenance. This inventory has been conducted inside the study area in order to categorize roads, identify drainage structures, rate their condition and maintain information related to the condition of the road surface.

The most important characteristics of each forest road have been collected and organized in a *geo-database* structure. The surveyed information was as followed: road width, surface type, surface condition, traffic limitation, presence and efficiency of drainage structures, functional and operative classification.

To estimate the maintenance needs the drainage system and the surface condition have been visually evaluated and rated as reported in Table 24.

Table 24 – Adopted code in the evaluation of the road conditions

Drainage structure		RATE	OPERATION
Present and functional	The drainage system does not need maintenance.	0	NO
Present and not functional	The drainage system needs immediately maintenance.	1	A
Missing	The drainage system is missing	2	D
Surface condition			
Regular	The road surface is functional and the trafficability is efficient. Road perfectly fits its preeminent function. No evident sign of erosion nor potholes.	1	NO
Partially damaged	Minor rilling is present on the surface. The condition slightly affects the trafficability. Potholes and erosion process are present but not very evident. The road needs ordinary surface maintenance intervention.	2	B
Damaged	Severe rilling is present on the surface. Trafficability is affected and sometimes the road cannot perform its function. The road needs a non ordinary surface maintenance intervention.	3	C

The cross-drain culvert's spacing is calculated in relation to the road gradient using the following formula as reported in the Forest Road Manual (AA.VV, 2000).

$$CS = 800 / Slope$$

The number of cross-drain structures, where missing, is then calculated considering the length of each road segment. The result has to be considered only as an indication; detailed placement of cross-drainage culverts has to be evaluated with consideration of site-specific conditions.

The evaluation of maintenance needs is conducted in order to understand the current state of the forest road network and the gap between current and optimal condition that represents the area in which the definition of the best maintenance strategy will be defined.
The output of the analysis is a map where all the possible maintenance interventions (alternatives) are reported. Maintenance interventions belonging to the same road have been grouped (a road is considered each section between two nodes) considering that the rational execution of the maintenance operations will interest a whole section. Each group of maintenance interventions belonging to each road represents one alternative in the definition of the ranking of alternatives.
Road maintenance activities normally performed in the studied area have been also analyzed. The maintenance operations have been divided into 3+1 basic types (Table 25): drainage structure cleaning, ordinary surface maintenance, non-ordinary surface maintenance and drainage structure installation.

Table 25 –Types of road maintenance operation performed and relatives costs

OPERATION TYPE	Operational details	Unitary cost	
A (Drainage structure cleaning)	2 operator	1.10	€ $*DS^{-1}*$
B (Ordinary surface management**): addition of crushed aggregate and consolidation	1 Tractor with grader 1 Truck for gravel transportation 3 Operators	1.21	€ $*m^{-1}$
C (Non ordinary surface management**)	1 Tractor with grader 1 Truck for gravel transportation Excavator 3 Operators	6.32	€ $*m^{-1}$
D (Drainage structure installation)	Excavator 2 Operators Materials	52	€ $*DS^{-1}*$

*DS: drainage structure (standard length of 5 meters)
** standard road width 3.50 m

All of the maintenance interventions that have occurred within the last 3 years have been monitored and mapped in order to determine the mean annual budget (constraint).
The mean cost for each type of operation has been also determined through project analysis (Table 14) and the derived cost have been used to calculate the economic resources needed to complete each intervention (alternatives) on the forest road network.
Additionally, the maintenance interventions have been divided into two groups according to the type of access of the roads. Public roads are open to all types of traffic (mainly for recreational purpose) and need to have high trafficability standards, whereas restricted access roads can be used only for forest management purpose and present normally the lowest trafficability standards and considerably less maintenance intervention.

4.3.5. Description of the GIS tools

All of the analysis have been supported by ArcGIS 10 (ESRI, 2010). The GIS methodologies utilized for the production of the priorities' definitions and the management indication maps are here explained.

Evaluation of the criterion map: different geoprocessing methods have been developed to determine the value of each evaluation criterion. All of these processes were finalized to produce a raster map with resolution of 5 m and with the same extension.
A geoprocessing tool has been created using Model-Builder to evaluate the gradient of the roads, using both the forest road network shapefile and the Digital Elevation Model as input. This tool uses the contour line as a basis for the calculation of the gradient.
In order to determine the level of traffic the flow direction and flow accumulation tools have been used. The transported volumes of logs on each road have been evaluated using the forest management plan data and the forest road network as input.
Finally, a terrain slope criterion map has been determined by extracting the values of the slope layer in correspondence to the roads.

AHP analysis: the spatial multi-criteria analysis has been supported from the use of a specific extension (AHP 1.1 – Decision support tool for ArcGIS) and has been developed from the *Institute for Applied Geosciences, Georesources and Geohazards* della *Technische Universität Darmstadt* (Marinoni, 2004a; Marinoni 2004b).
The extension allows the combination of the different criterion layers in raster format (Figure 44, a) thus defining the relative pair-wise comparison matrix (Figure 44, b).
Once the tool is run, a new raster layer is calculated as a weighted sum of the defined raster layers and added to the current ArcMap session.

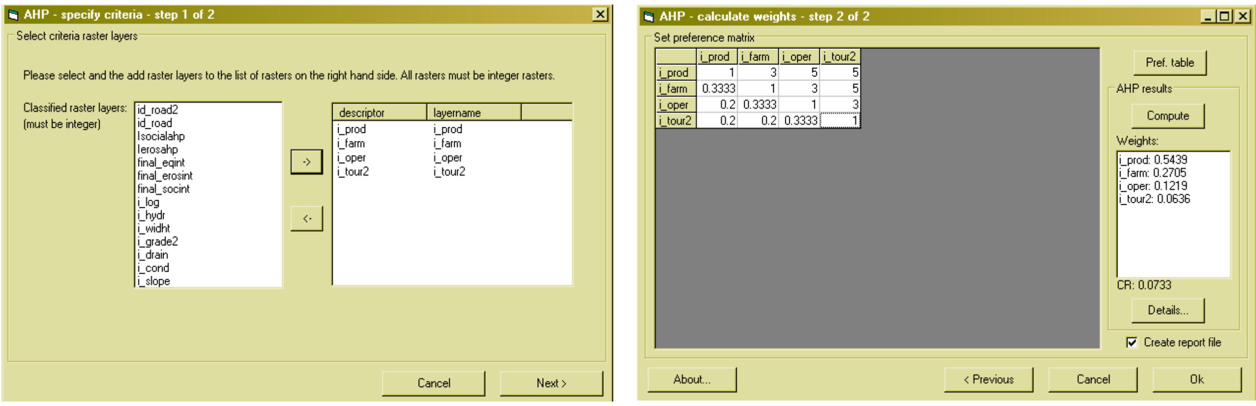


Figure 44 – AHP extension windows to specify criteria (a) and to define the preference values (b)

Zonal statistic: with the Zonal Statistics tools, statistics are calculated for each zone as defined by a zone dataset (eg. polyline features dataset) based on values from another dataset (eg. raster dataset). This functionality has been used to transfer the evaluation layer values to the forest road network polylines and calculate the relative statistic.

Network analyst: ArcGIS Network Analyst represents a valid tool to perform analysis and solve logistic problems. This tool allows the creation of an origin-destination (OD) cost matrix from multiple origins to multiple destinations, setting network impedance (such as travel time) from each origin to each destination. Additionally, it ranks the destinations such that each origin is connected in ascending order based on the minimum network impedance required to travel from that origin to each destination. The routing solvers OD cost matrix is based on the Dykstra's algorithm (DYKSTRA, 1984) for finding shortest paths (ESRI, 2010).
The network analyst tool has been used to analyze the accessibility of the forest road network and to formulate new management strategies. The inputs of the analysis were the access point to the area

(origin points), the point of interest, such as farming activity or touristic site (destination points) and the forest road network, where the considered network impedance values were represented from the erosion risk. Running the model determined the minimum extension of the forest road network that guarantees access to the point of interest (farming activity, touristic site) while at the same time minimizing the cumulated value of erosion risk.

4.4. Results

4.4.1. Alternatives definition and maintenance cost analysis

The field survey highlights that the 12% total extension of the forest road network requires no maintenance intervention while the remaining 88% does require maintenance.
Identified maintenance interventions found 390 distributed interventions on 44 road segments. The sum of the maintenance interventions on each road segment represents one alternative. The majority of the maintenance operations involve the improvement of the drainage system, including the installation of new structures (53% of the total extension) and the cleaning of the existing ones (23%). Surface maintenance is required on 11 road segments (20%).
The total estimated investment to complete the maintenance of the project was 68 297 €. Table 26 shows the number of needed interventions and the estimated budget to complete all the projects.

Table 26 - required maintenance interventions and estimated costs

OPERATION TYPE	N INTERVENTIONS	TOTAL COST (€)
A (Drainage structure cleaning)	98	107.8
B (Ordinary surface management)	6	10 350
C (Non ordinary surface management)	5	34 617
D (Drainage structure installation)	281	14 612
TOTAL	390	68 297

During the monitored period, 2008-2010, the management authorities made 27 maintenance interventions on the forest road network of the area. In total, there have been 30.7 km of roads maintained, with a total expense of 87 000 €.
According to this, the assumed annual budget for ordinary maintenance will be 29 000 € (*budget constraint*).
The analysis of the distribution of maintenance operations executed from the management authorities in the last three years, with respect to the type of access, highlights a concentration of the interventions on the public (open access) roads. Comparing the total extension of gravel road with the total investment in maintenance operations, both for public and restricted access roads, two indexes of maintenance costs have been derived (Table 27). All maintenance costs have been capitalized to present.

Table 27 – Maintenance cost indexes considering the type of access

Gravel road		*Intervention*		*Total cost*	
	km	*N*	*km*	*€*	*€*m*y⁻¹*
Public road	48	24	22.1	77 900	0.54
Restricted access road	35.8	3	8.6	8 700	0.09

4.4.2. Rating and ranking of the alternatives

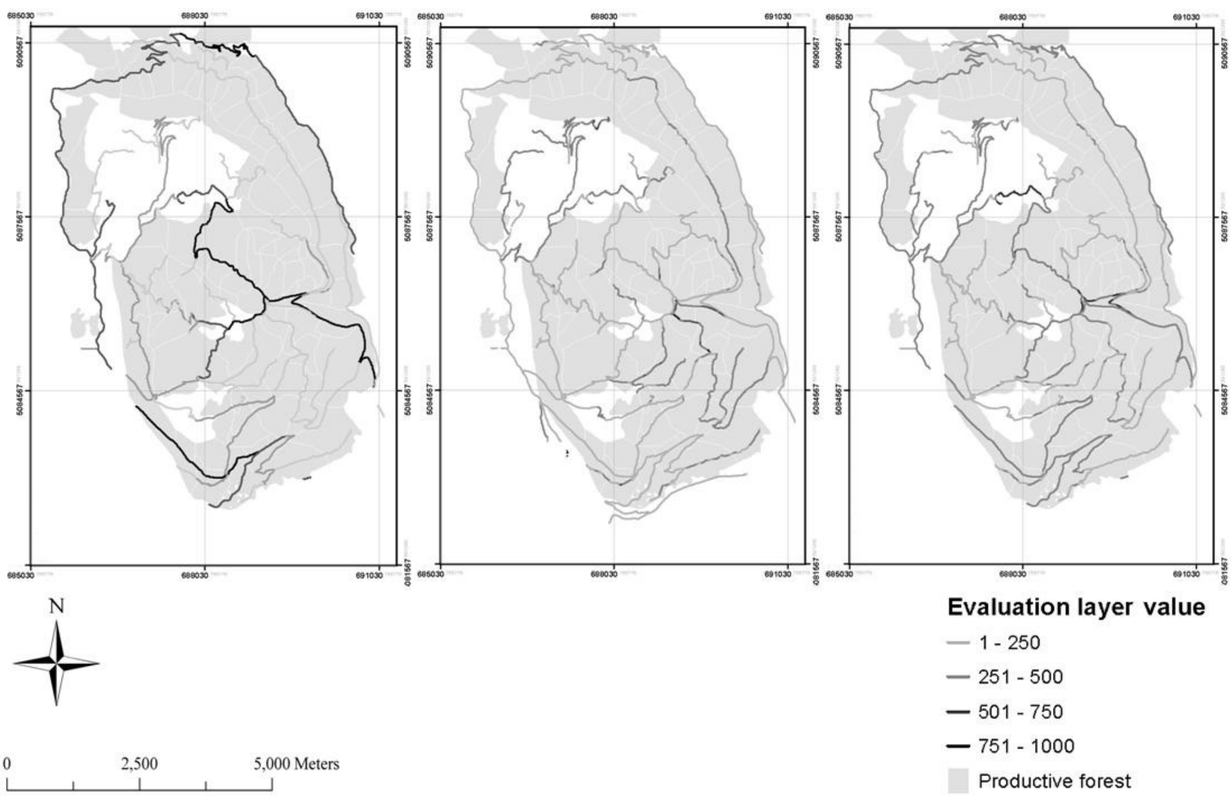
Table 5 shows the output weights reported of the different factors taking into consideration after the AHP pairwise grid evaluation.

Table 28 – Criterion weights as resulted from pairwise grid evaluation

Objective 1: Road surface erosion risk		Objective 2: Road social value	
Sub-criteria	*Weight*	*Sub-criteria*	*Weight*
*i*GRADE	0.5661	*i*TOUR	0.4236
*i*DRAIN	0.2012	*i*OPER	0.2903
*i*COND	0.1319	*i*FARM	0.1745
*i*SLOPE	0.1007	*i*PROD	0.1114
Consistency ratio* (CR): 0.0434		Consistency ratio* (CR): 0.0750	

*Revision of preference values is recommended if CR > 0.1

Application of the spatial AHP analysis leads to the production of the two raster layers that present for each cell the benefit score referring to the relative objective.
The combination of the two layers at the highest level of the AHP analysis produced the final evaluation layer that represented the overall benefit score for each cell.
The evaluation layer maps resulted from the application of the AHP process are represented in the following pictures (Figure 45).



(a) (b) (c)

Figure 45 – Maps representing the different evaluation layers: social value (a), erosion risk value (b) and combination of the two objectives (c)

The correspondence with reality, the erosion risk value layer, has been evaluated through field surveys. In particular, the value evaluated was assumed by the index at points in the field where the presence of erosion has been detected. Out of the 51 erosion points, 28 points were located in positions that present high erosion risk values, 20 had medium risk values while 4 points were in the low risk value range.
The distribution of the survey points highlights a good correspondence of the index to reality.
Through the use of the zonal statistic tool, the cell values on the evaluation layer have been summarized within the forest road network features and the statistics relative to the benefit value of each road have been calculated.
Table 29 is an example of the attribute table of forest road network features after the application of the AHP analysis. Roads (ROAD ID) are ranked according with their benefit value, where SED_RISK represent the risk value of sediment production from the road surface, SOC_VAL represent the social value of the road and EQ_VAL represents the combination of the two values (evaluation layer). C1, C2 and C3 represent the costs of the different maintenance operation while TOT_COST represent the total cost to upgrade the road.

Table 29 - Attribute tables of the forest roads network features

RANK	Road ID	SED_RISK	SOC_VAL	EQ_VAL	C1	C2	C3	TOT_COST
1	50	391	627	509	312	0	0	312
2	35	259	663	461	312	0	1388	1702
3	37	230	649	440	104	0	0	104
4	41	200	573	387	312	918	802	2032
5	58	253	484	368	104	834	0	938
6	40	391	302	347	624	0	7256	7880
7	30	403	198	339	728	0	7713	8441
8	38	307	288	305	1976	0	1693	3669
9	53	406	442	302	936	0	7565	8501
10	28	309	259	298	104	0	0	104
11	42	154	215	281	104	0	0	104

4.4.3. Definition of the optimal maintenance and management strategies

Information contained in the table can be used to define the priorities in orientating maintenance intervention and rank the alternatives that have to be founded. Road that present an higher erosion risk requires more efforts to be maintained in good condition while according with the importance for the accessibility of the territory, roads with an higher social value should be preferably maintained in good condition.
Figure 46 shows the mapping of the forest road network highlighting the parts that will be maintained with the budget of 29 000 € for ordinary maintenance, in accordance with the different objectives.
When only the social value of the roads was considered, the interventions found require an extension of 40 km of which 31 km (77 %) are open to traffic.
Considering only the minimization of the erosion, the maintenance will require 8.5 km of which 4.2 (49 %) are open to traffic. In this case, maintenance is concentrated on few roads that are evaluated as more problematic as the condition of the road is critical and maintenance interventions are more expensive.
Finally, in the case of an equal consideration of the two objectives, the maintenance interventions will include an extension of 29 km of which 25.5 km (89 %) are open to traffic.

Having also evaluated the correspondence between the priorities resulting from the elaborations and the actual maintenance strategies, the highest correspondence (65 %) is reached with equal consideration of the two objectives, where 18.8 km of the road considered priority has had maintenance intervention in the last three years. In contrast, the consideration of the erosion risk has the lowest correspondence (25 %) with the 2.2 km that have been maintained. Finally, when the priorities defined considered only the social value, a correspondence was found of 56 % with 22.7 km that have been maintained.

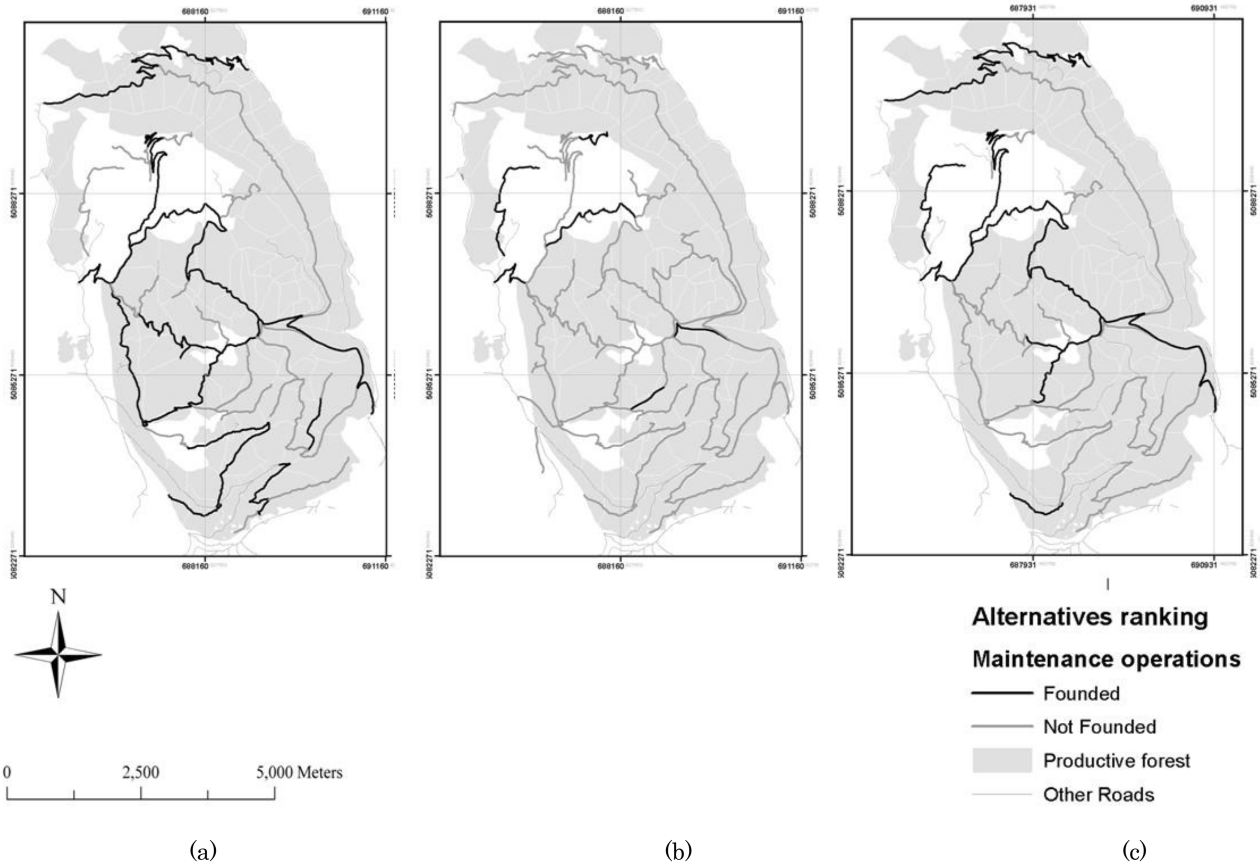


Figure 46 - Maps representing the alternatives ranking for the different objectives: social value (a), erosion risk value (b) and combination of the two objectives (c)

A choice of opportunities over the existing forest road network mainly regards the management options. In particular, the management authorities can set the access regulations. Road access management is necessary to help meet management goals and objectives as well as to reduce maintenance costs and sediment loads through restricting traffic.

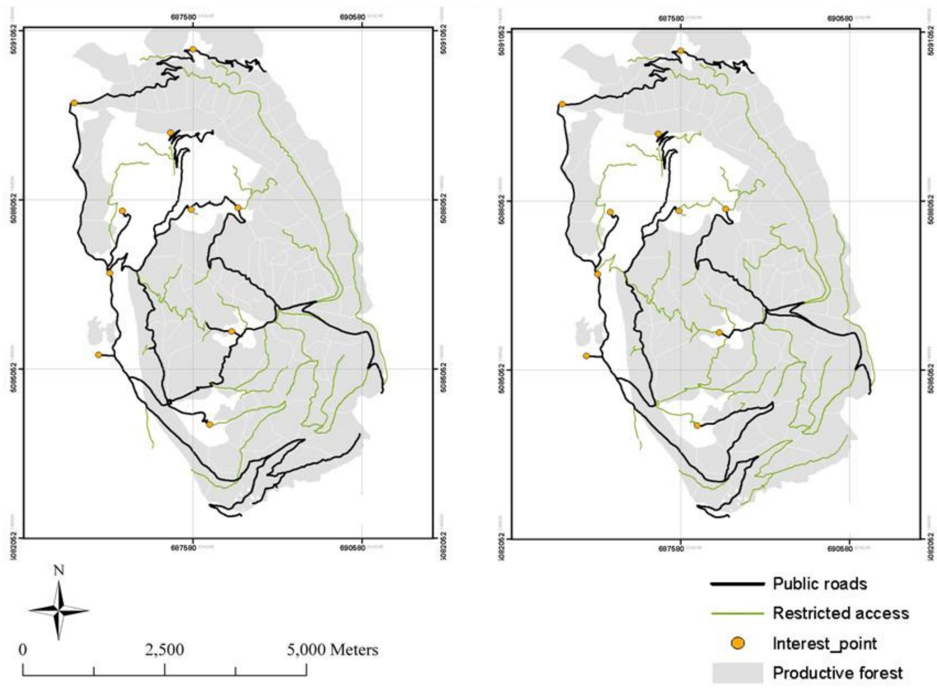
The benefit score that resulted from the AHP analysis has been used to study the optimal management strategies of the forest road network. In particular, the opportunity of modifying the road access management in order to reduce maintenance cost has been investigated.

Public roads present the highest maintenance costs and highest environmental impacts, and for these reasons should be limited to the minimal level that meets the accessibility needs of the region.

Using network analyst tools, the minimum extension of the forest road network that guarantees access to the point of interest (farming activity, touristic site) while minimizing the risk of erosion has been evaluated.
A model of the forest road network has been built and a Closest Facility analysis has been ran. The inputs for the model are represented by the access point (origin), the point of interest (destination) and the forest road network.
The model calculates the shortest path to reach each destination from each origin while minimizing the cumulated value of the erosion risk. From the resulting matrix, the shortest path to reach each destination has been chosen (output of the model). The identified sets of road have been hypothesized to be the optimal level of public (open access) road (Figure 23).
In Table 30 the results of the analysis are presented. In the optimal situation, the public road extension has been reduced by 17 % with a reduction of the yearly maintenance expense equaling 3 915 € (-13 %) and a reduction of the cumulated erosion risk index of 20%.

Table 30 – Results of the forest road access strategies analysis

	Road network		Supposed yearly expense	Cumulated erosion risk index
	Public km	Limited km	€	
Scenario 1 – Actual situation	49.7	37.8	30 240	11 714
Scenario 2 – Optimal situation	41	46.5	26 325	9 328



a) b)

Figure 47 - Distribution of public and restricted access road in the actual situation (a) and in the optimal (b)

4.5. Discussion and conclusion

The economic resources necessary to completely upgrade the forest road network are equal to 67 000 €. Additionally, the yearly ordinary maintenance costs were 30 240 €. These values highlight the inadequacy of the current annual budget to meet the maintenance requirements of a forest road network in the mountains.

The lack of economic resources affects the "*modus operandi*" of the management authority that constantly needs to choose which roads to keep in good condition. The current strategy guarantees constant maintenance mainly on the roads open to traffic where road standards and level of trafficability need to be higher.

Field surveys suggest that the management strategy needs to be reconsidered. Erosion and consequent production of sediment from the gravel road surface is a frequent process over the entire area and directly connected with worsening condition of the roads. In particular, the general lack of drainage structures seems to be one of the most important factors that lead to a consistent delivery of sediment from forest road surface.

Because of this situation, the opportunities for structural improvement of the management strategies have been evaluated.

In this context the integrated use of GIS and AHP analysis has been proven to be a valuable tool to better understand the ongoing processes and to give indications to determine the maintenance operations.

The proposed method integrates through the pairwise comparison process two different aspects, the evaluation of the erosion risk and the evaluation of the social value of the roads considering a total of 8 criteria. Additionally, the model can be adapted to the preferences of the stakeholders who can specify which function of the forest road network should be considered preeminent as per the specific vocation and needs of the analyzed area.

The resulting evaluation layer has been used to understand the benefits of the required maintenance operations and to define the ranking of the priorities.

The distribution of the priorities considering the combination of the two objectives justifies the maintenance strategy currently practiced, as it indicates that the available budget (29 000 €) would be in large part (89 %) destined for the maintenance interventions on the public roads, and that 65 % of the resources will involve roads that have been recently maintained. On the other hand, the risk of erosion seems to be considered less as only the 25 % of the road with high risk of erosion has been recently maintained.

The study of different management strategies to reduce maintenance costs took into consideration the possibility to reduce the number of public (open access) roads as these have been proven to present higher maintenance costs. The extension of the public roads that minimize the cumulated value of erosion risk while guaranteeing access to all sites of interest, has been determined by modeling the road network with Network Analyst. Public road extensions have been reduced by 17 % with a reduction of the yearly maintenance expense equal to 3 915 € (-13 %) and a reduction of the cumulated erosion risk index of 20 %.

In conclusion, the use of integrated GIS tools and AHP analysis shows that different aspects can be effectively integrated. Consequently, the approach could be used to improve the effective administration and management of maintenance planning, especially considering that existing forest road system needs to evolve toward a paradigm where other benefits (e.g. recreational value) and priorities (e.g. environmental aspects) are included and methods for consideration of these objectives must be developed.

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Attachement

Four papers, dealing with studies carried out simultaneously to the present work, with the purpose of acquiring useful information to its development or as result of the application of the developed methodologies and the acquired data are attached.

The first one "*GPS mobile devices and open source GIS: a comparison between different solutions*" reports the results of a test that was carried out using different available GPS tools and GIS software in order to verify the possibility of using technology and software at low or zero cost to collect and analyze data useful for the planning of forest operations. This work is thus useful to understand the capability and the limit of the different tools that can be used also for the management of a forest road network. The work have been published in the proceedings of the international conference "FORMEC 2009".

The second one *"The evolution of a mountain road network from the original war-use to the forest one and its current management"* uses the data contained in the forest road network geo-database to investigate the technical evolution of a mountainous road network for forest operation and forest activities from the beginning of the last century to nowadays.

The third one "*Determination of the forest road network influence on the supply chain for firewood production by discrete Event simulation*" aims to develop a D-es model for evaluating the productivity of the wood supply chain for firewood production from the harvesting site to the firewood production terminal, considering different scenarios according with the extension of the transportation network. This work represents a first example of how the availability of detailed data about forest roads can be used as basis for the application of a methodology (D-es)

The last one "*A strategy for the management of abandoned mountain pasture land colonised by Dwarf pine*" analyzes the logistic problem related to the harvesting and the transport of the wood material resulted from the reclamation of mountain pastures. The logistic problem is broadly analyzed using a GIS-based decision support system based on a network analysis model and assuming various scenarios associated with different levels of upgrade of the forest road network. Again the transportation model uses the data contained in the forest road network geo-database as input.

GPS mobile devices and open source GIS: a comparison between different solutions

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Abstract: *Planning forest operation require detailed support information to correctly characterize fundamental element such as forest road network and terrain features. Data survey and analysis often require also considerable investment both in terms of time and money. The purpose of the study is to verify the possibility of using technology and software at low or zero cost for planning forest operation. To achieve this result a real test was carried out using different available GPS tools and GIS software.*
The procedure consisted on field GPS surveys of forest road network and terrain roughness in a mountainous area in the Northern-East part of Italy. The collected data was then used for GIS-based analysis for settling on the forest operation plan using different software.
It was evidenced that professional and commercial technologies and software, required really high investment but also bring to high quality results and allows simple and fast workflow. Low investment or freeware solution can even support forest technicians, allow a considerable saving of money, but taking into consideration that the workflow often will result more elaborated, less simple, accurate and more time-expensive.

Keyword: GPS, GIS, forest road, forest operation

1. Introduction

Forest road network analysis represents a fundamental element in order to evaluate forest accessibility for cost estimation in relation to an applied transport system.
The use of GIS-based analysis integrated with GPS or routing surveys over forest road network can add an enough accuracy level in order to characterize the same forest road network according to transport systems. GPS receivers are frequently useful to forest management activities related with locating or mapping boundaries as monitoring harvesting machinery (McDonald et al., 2002), topography and cadastral forest surveys (Yoshimura et al., 2002), forest inventory, resources and special management areas (Wing and Kellogg, 2004), forest area and perimeter estimation (Tachiki et al., 2005) and GIS forest applications (Wing and Bettinger, 2003).
In forest management two type of reliefs can be distinguished: the topographic relief and the descriptive relief. The topographic reliefs require high precision tools whereas the accuracy required by descriptive relives can call for the use of consumer grade tools which are considerably less expensive but guarantee a sufficient level of precision.
The use of GPS receivers is constantly increasing especially because of the extended use of this technology in many outdoor recreational activity. According with this assumption also the characteristics of the GPS receivers have seen an evolution, becoming more accessible to a wide range of users and with prices often very cheap (*consumer grade* GPS). GPS receivers can generally be classified into three grade: *survey*, *mapping*, and *consumer* grade. Survey grade GPS is capable of determining locations to within 1 cm of true positions (sub-metric precision) (Rizos 2002), but it requires operator expertise and a substantial operating budget because of the high costs of the instrument (from 15 000 €). Survey grade GPS also requires satellite signal reception that is often unattainable forest canopy. Mapping-grade GPS receivers can return accuracies typically within 2-5 m of true position (metric precision), depending on the quality of the equipment and operator skill, with instrument cost ranging from 1500 to 11 000 €. Although mapping-grade GPS can be somewhat less demanding than survey grade in terms of acceptable satellite reception and required operator skill, the price of there units can be still high to many potential user.

In contrast, consumer-grade GPS receivers are now available at prices less then 200 € and there are many different manufacturers and styles of consumer-grade GPS receivers. Consumer-grade GPS manufacturers commonly assert that measurement accuracies of this equipment should be within 15-20 m of true position. Wing (2005) indicates that the positional accuracies of consumer grade GPS receivers are better than 15-20 m range often cited as a yardstick. It is also known that the positioning precision and accuracy under forest canopy are markedly lower than in areas with open sky condition because trees attenuate or stop GPS signals. Wing and Eklund (2007) highlight that the overall average positional error for the consumer grade GPS can be larger than that of the mapping grade GPS but the consumer grade GPS collected data more efficiently.
Commonly, after GPS surveying, the acquired data are processed by differential correction and afterwards uploaded into geodatabase and eventually processed by GIS software. Working with GIS and geodatabase is a complex operation which involves data capture, verification and structuring process. Because raw geographical data are available in many different analogue or digital forms (such as maps, aerial photographs, satellite images, table and information acquired by GPS) a spatial results can be reached in several but not mutually exclusive ways by GIS software and their given extensions or tools (Burrough and McDonnell 1998). Nowadays many GIS software are available both with commercial licence both freeware or open source. Some of the commercial license GIS software are also developed *ad hoc* and exclusively for forest management.

1.1 Aims

Aim of the study is to compare the use of a *mapping grade D-GPS receiver* with a *consumer grade GPS receiver*. The comparison, based on the accuracy level reported by the two GPS receivers, concerns the survey of interest points along a forest road network in mountainous condition under broadleaves and coniferous stands. Afterwards the collected information are used in order to map the forest area according to the most suitable extraction system in relation to forest road condition, terrain morphology and forest yield. The elaboration is supported by a *commercial* GIS software and the procedure is compared with the possibility to use, according to their tool and extension, different *freeware* or *open source* GIS software.

2. Material and methods

2.1 Study area

Study area is located in Northern-east part of Italy at latitude (N) of 5078238 – 5076128 and longitude of 689186 – 691176. Altitude of the area rises from 969 to 1344 m a.s.l. The most represented forest species are beech and spruce. Total forest area range over 240 ha and it is divided into 4 forest plots. High forest treatment is spread in part also to broadleaves as in the last years a part of coppice area has been converted to high forest. Forest road network (permanent) extension is 8.4 km and forest road density index reaches 35 m/ha. By including also temporary forest road network, the forest road density reaches 41 m/ha.

2.2 GPS and GIS tools

To evaluate the differences in the application of different GPS receivers and different GIS software two workflows (*high investment* and *low investment*) have been carried out for the same planned procedure of analysis. High investment workflow considers the use of mapping grade D-GPS with commercial GPS software and the data and geo-analysis processing by commercial software. As an alternative the low investment workflow considers the use of consumer grade GPS receiver as smart-phone with freeware GPS software and the data and geo-analysis processing by open source and freeware software (Table 1). Both the GPS have twelve channel receiver.

Table 1. GPS and GIS software used on the high and low investment surveying and analyzing procedures

PROCEDURE		High investment (mapping grade GPS, commercial software)	Low investment (smart-phone, freeware/open source software)
Main steps		GPS receiver and GPS/GIS software	
1.	Data collection and first investigation	Arc GIS 9.2. (GIS commercial software)	SAGA, QGIS, OpenJump, GvSIG (GIS freeware and open source software)
2.	Surveying	Topcon GMS-2 (Mapping grade D-GPS receiver) Mercurio (GPS commercial software)	HTC3300 (Smart-phone with GPS receiver) NoniGPSPlot (GPS freeware software)
3.	Post-processing	Meridiana (GPS commercial software) Arc GIS 9.2 (GIS commercial software)	DNR Garmin (GPS freeware software) SAGA, QGIS, OpenJump, GvSIG (GIS freeware and open source software)
4.	GIS-based analysis	Arc GIS 9.2 (GIS commercial software)	SAGA, QGIS, OpenJump, GvSIG (GIS freeware and open source software)
*ArcGIS 9.2. included all the following extension ** OpenJump works only with vector data			

The study is subdivided in four main steps:

1. Data collection and first investigation of the area: necessary information have been acquired, rearranged and displayed in order to print support map useful during the relief and to the geo-spatial analysis. Forest road network was extracted from the Regional Technical Map (CTR – available on vector format *.dxf* and based on 1:10 000 scale) and converted into *.shp* and *.gpx* format. Also the Digital Elevation Model (DEM) was derived as Triangulated Irregular Network (TIN) surfaces from contours and altitude points with elevation information extracted from the CTR. Therefore the TIN-DEM (resolution size 10 m) was converted into a raster through interpolation and converted in *.tiff* or in proprietary file.
   Forest stand information were derived by the regional Forest Management Plan, available in *.shp* format. The aerial orthophoto were converted from *.ecw* to *.tiff* and *.jpeg* formats in order to be visualized by the GPS software. Data on forest road characteristics and terrain roughness were not available;

2. Surveying: GPS surveys have been carried out contemporaneously with both GPS receivers to guarantee identical surveying conditions and comparable results. Maximum slope gradient, minimum width, location and dimensions of the landings in the forest road network were collected by point survey in order to classify each roads according to accessibility and transportation. All the forest road network was covered and the missing tracks were updated by continuous GPS surveying. Forest roads were then classified into five different accessibility and transportation class according to the collected information.
   To analyze terrain roughness the whole area was divided by GIS software into a fishnet of square cells with a size of 50 m thus defining a regular square sampling net (Köhl, et al. 2006)**.** The ground roughness was defined by field observation within each square cell considering the obstacles of more than 50 cm height or depth and on the distance between the same obstacles (when it is less than 3 m). Inside each square a point was surveyed with both the GPS receivers. The ground roughness index was reported for each point according to three classes: no ground roughness (occurrence of obstacles in 1/3 of the cell area), smooth ground roughness (occurrence of obstacles in 1/3-2/3 of the cell area) and high ground roughness (occurrence of obstacles in more than 2/3 of the cell area) (Sundberg and Silversides, 1998);

3. Post processing: GPS data have been downloaded into a PC (HP Compaq, Intel® Core™ 2 Duo CPU E8400 @ 3.00GHz-1.98GHz, 2.00GB of RAM). Format output of the mapping grade GPS software was a proprietary format and the visualization and transformation into *.txt* or *.shp* format could be possible through the commercial

software supplied with the receivers. The freeware GPS software data format was easily exportable in *.txt* (or *.gpx or .kml*) format and consequently converted into *.shp* format by another freeware software. The data collected by mapping grade D-GPS was post-processed by differential correction also by the same supplied commercial software. Instead there was no possibility to correct the information surveyed by the consumer grade GPS;

4. GIS-based analysis: by elaborating the Digital Elevation Model, forest road network, forest management plan and GPS surveyed data different raster elaboration were performed in order to classify the forest area according to the most suitable extraction system (Cavalli et al. 2006). Elaboration was performed using different GIS software as reported in Table 1.
   Three extraction system were considered: transport by forwarder, skidding by agriculture tractor or forwarder equipped with winch and working on skidder trail and extraction by mobile tower yarder (all terrain system). In the study area the use of forwarder is becoming common therefore when the ground roughness and the terrain slope are adapt, forwarder will tend to replace the skidding operation performed by farm tractor. When ground roughness is high, forwarder or agriculture tractor (both equipped with winch) will work on road side or on the skidder trail, pulling logs by winch within 50 to 80 m (depending on slope gradient and local terrain condition). In the area cable system extraction are not so common because of the low density of cuts and the small tree size.
   The GIS analysis on extraction system was based on a raster elaboration by logical operations through the standard rules of Boolean algebra (Burrough and McDonnell, 1998). Table 2 reports the parameter used in the calculation in order to obtains extraction maps both (depending on the GIS software) in *proprietary format* and in *.tiff* format.
   Ground roughness map was defined by a geospatial interpolation from the 650 surveyed points. The used methods was the *Ordinary Kriging* (OKr) as it is included in 4 of the 5 exploited GIS software. OKr is an exact interpolator where the interpolated values, or best local average, will coincide with the values at the data points (Burrough and McDonnell, 1998; Köhl et al., 2006).

Table 2. Parameter used in the calculation settled to obtains extraction maps

Extraction system	Ground roughness	Extraction distance		Slope gradient	
		Up-hill	Down-hill	Up-hill	Down-hill
		m		%	
Transport by forwarder	low	350	350	35	35
Skidding to skidder trail or forest road by tractor and winch	medium	80	50	40	20
Mobile tower yarder	high	300	300	100	100

3. Results

3.1 GPS applications

The coordinate of the point surveyed with the mapping grade GPS were corrected by post-processing elaborations. The points collected by consumer grade GPS were not corrected as it was not possible. On table 3 is reported the average error distance of the coordinate X and Y in respect of the values of the coordinate of the points which were corrected by post-processing differential correction.

Table 3. Average errors of the coordinate points of the two used GPS systems in respect of the *differential correction processing* to the surveyed points of the mapping grade D-GPS

Type of the survey	Canopy	Mapping grade D-GPS *(with no diff. correction)*		Consumer grade GPS	
		X	Y	X	Y
		m	m	m	m
road network: point of interest	generally treeless	± 5.94	± 6.25	± 10.21	± 9.53
ground roughness	closed	± 9.14	± 8.37	± 10.97	± 9.97

3.2 GIS software application

Different GIS software were tested and evaluated in terms of user friendliness and quality of the process (Table 4). The commercial GIS software offer different solution process and tool easy to use and with good quality of the process. Two of the open source GIS software (*SAGA and Q-GIS*) show tools and processes useful for forest operation investigation (commonly specific for raster analysis) as for updating forest road network or fighting fire database (commonly vector data management). *OpenJump* presents simply and clear tools for vector data management but it misses tool and process for raster analysis. The last release of *GvSIG* is actually instable and it is unreliable even if it presents interesting tools and processes both for raster and vector data management and analysis, whereas the commercial software (ArcGIS 9.2) is definitely the most friendliness and complete in number of tools and capacity of analysis (Figure 2).

Table 4. Evaluation of the GIS software application: G-good, D-discrete, L-lacking because of software bugs, NA-not available process

	commercial	*open source/freeware*			
	ArcGIS 9.2	GvSIG	SAGA	Q-GIS	OpenJump
Creation of the DEM	G	L	G	G	NA
Updating forestry road cadastre	G	D	D	D	D
Creation of terrain-roughness map	G	L	D	D	NA
Creation of terrain-slope map	G	D	G	D	NA
Distance calculation (down-hill *vs* up-hill)	G	L	D	D	NA
Elaboration of extraction map (map calculator)	G	L	D	G	NA

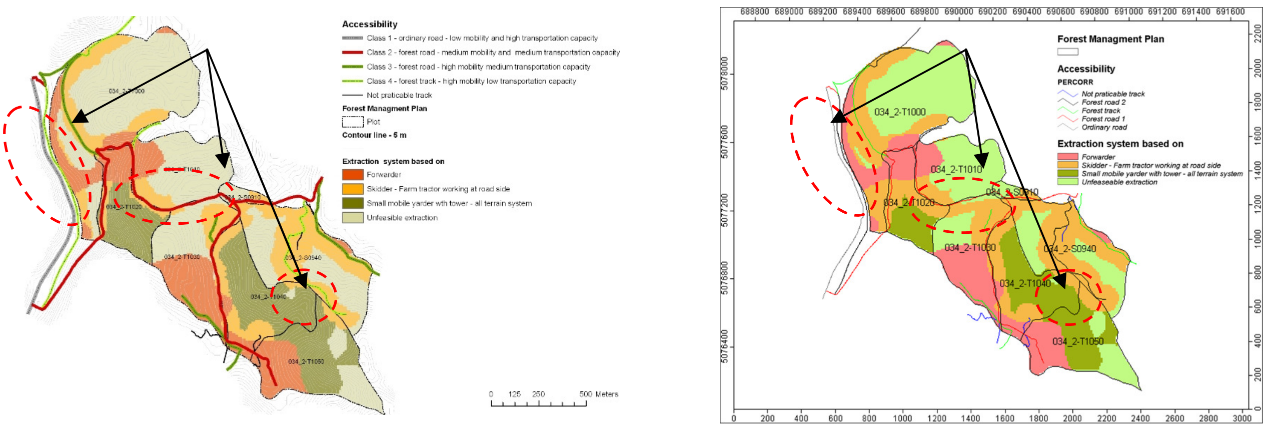

Figure 1. Resulting map on extraction system analysis by using ArcGIS 9.2 *commercial* GIS software (left) and by using SAGA *open source* GIS software (right): differences in the resulting maps are also highlighted

4. Discussions and conclusions

The present work tests the limits of GPS mobile devices and GIS technology and software at low or zero costs for planning forest operation. The analysis highlights the currently availability of different combined system for surveying and analyzing data in forest activity. Professional and commercial technologies and software bring to high quality results and allows simple and fast workflow. Low investment or freeware solution can even support forest technicians, but taking into consideration that the workflow often will result more elaborated, less simple and precise (Figure 2) and more time-expensive.

Consumer grade GPS points out fairly good results as the level of the precision is low even if it can be considered enough for a quick collection of information useful for a raw geographical representation of a investigated forest area. As a consequence, the use of consumer grade GPS can have a sense if the survey is not finalized to a detailed forest operation plan.

Major problems arise at the level of GIS based elaboration. Open source GIS software often missed in implemented tools or implemented tools are lacking because of software bugs. Consequently the GIS-based analysis became more complicated or even impossible. In this case the limits of the use of open source GIS software can be resolved by expert GIS users and programmers. The commercial software even if reports and high level of user-friendly and capacity present high costs which often are unaffordable for small forest consulting enterprise.

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The evolution of a mountain road network from the original war-use to the forest one and its current management

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Abstract: *In some mountain areas located in Northeast Italy the present forest road network has been partially developed using the previous military road network built during the First World War (1st WW). The current management of the forest areas considers road network essential to provide access for the forest operations but also to increase the value of recreation activities and historical tourism regarding the heritage value of the areas.*
Aim of the study was to investigate the technical evolution of a mountainous road network for forest operation and forest activities from the beginning of the last century to nowadays. The research consisted on a preliminary reconnaissance of the original road network using the 1st WW military maps, a further reconnaissance using the technical maps dated to the 60's of the last century and the survey of the current road network through GPS.
Furthermore the study aimed to evaluate the current condition of the original road network according to its current use in order to highlight the influence between the building standards of the roads and the evolution in terms of transportation system and traffic management.

Keywords: road network, mountainous areas, historical road, 1st WW

1. Introduction

During the First World War (1st WW) period most of the front between Italian and Austro-Hungarian Armies lay on the Alpine areas. Due to the lack of transportation infrastructures both the Armies were forced to design and build a wide road network necessary for troops displacement and material supply (only on the really steep areas cableway systems were used). The technical features and the material used to build such road network (Figure 1) were so well fit that most of the roads are still present (Figure 2) and they are used mainly as forest road network.


Figure 1. Italian soldiers gravelling a new built military road


Figure 2. Present condition of a well preserved military road

2. Aims

The purpose of this study is to investigate the improvement of the transport network from the beginning of the 1st WW to the existing road network within a mountainous forest area and to evaluate the condition of the original transport network according to its re-engineered condition and its current use.

3. Material and Methods

3.1 Study area

Study areas are located in the Altopiano dei Sette Comuni in the North-eastern part of Italy. It represents a meaningful case study for the analysis of the expansion of the transport network from the 1st WW to the current forest road network (Cavalli et al. 2010). Two forest areas were identified, differing mainly by the average slope gradient of the terrain and with the same extent of forest area and almost the same area managed through Forest Management Plans (Table 1).

Table 1. Main characteristics of the two study areas (A: area, FA: incidence of the forest area; MF: managed forest; MT: main tree species)

Study area	A	FA	MF	MT	Slope gradient	
	ha	%	%	-	% (mean)	% (St.Dev)
Verena	5776	86.7	80.8	Spruce and fir	40.3	14.26
Boscon	3372	86.8	86.8	Spruce and beech	28.8	31.37

The Italian Army at the beginning of the 1st WW controlled both the areas. In the Verena area were located two important Italian fortresses and the transport network was designed mainly to provide logistic access to this places. Boscon area remains under Italian possession during all the 1st WW while Verena area was occupied by Austro-Hungarian Army from May 1916 until the end of the war and during this period transport network was improved.

3.2 Current extension of the road network

In the areas, the road network differs greatly due to its development through time and layout over terrain. The geographic patterns of roads in forest landscapes can differ substantially from place to place, with commensurate differences in operational level. Nevertheless, the awareness of the extension of the forest road network, by excluding road with dominant public use, is deficient in technical descriptions. For these reasons between 2010 and 2011 the forest road network of the two areas was surveyed using a professional GPS (Trimble Pathfinder ProXH). Therefore each road segment was classified according to its main use (Table 2) and its operative level (Table 3).

Table 2. Road classification according to its use

Class	Function	Description
O	Ordinary roads	National and regional major roads generally not used for forest purposes
C	Access roads	Principal and roads rarely used for forest purposes
MF	Multi-function roads	Secondary roads with free access commonly used for rural, forestry or recreational purposes
FOR	Forest roads	Forest roads with free or restricted access for forestry purposes
NC	Not classified	Network of not permanent skid roads or trail not practicable with vehicles, including also recreational trails

Table 3. Road classification according to its operative level

Class	Description	Forest operations
1	Low mobility and high load capacity	Truck with trailer
2	Low mobility and medium (+) load capacity	Truck
3	High mobility and medium (-) load capacity	Forwarder or tractor with forest trailer
4	High mobility and low or null load capacity	Small tractor with single axe carriage
0	Not permanent skid roads or trail not practicable with vehicles	

3.2 Historical maps

In order to analyze the evolution of the road network in the two study areas, a first research on the availability of historical maps and aerial-photos has been carried out. To guarantee the standardization of the data, the research considered the use of historical maps with the same scale, the same revising time and the same origin. According to these remarks, 9 historical maps of the *Carta d'Italia,* upgraded during the 1st WW for military use, were collected from the Biblioteca Civica Bertoliana (Vicenza) (Table 4).

Table 4. List of the collected and georeferenced historical maps for militay use

Code	Map	Scale	First survey	General Reconnaissance	Upgrade
Conco	Sheet 37 Carta d'Italia Sez. III.N.E.	1:25000	1887	1910	15.8.1917
Valstagna	Sheet 37 Carta d'Italia Sez. IV.S.E.	1:25000	1886	1910	15.8.1917
Asiago	Sheet 37 Carta d'Italia Sez. IV S.O.	1:25000	1886	-	-
Monte Lisser	Sheet 37 Carta d'Italia Sez. IV N.E.	1:25000	1886	-	15.8.1917
Cima Dodici	Sheet 37 Carta d'Italia Sez. IV N.O.	1:25000	-	1910	15.8.1917
Monte Verena	Sheet 36 Carta d'Italia Sez I. N.E .	1:25000	-	-	15.8.1917
Rotzo	Sheet 36 Carta d'Italia Sez I. S.E.	1:25000	1886	1912	15.8.1917
Caltrano	Sheet 36 Carta d'Italia Sez III. N.O.	1:25000	1887	-	15.8.1917
Arsiero	Sheet 36 Carta d'Italia Sez II. N.E.	1:25000	1886	1912	31.5.1917

The collected maps reported a considerable numbers of geographic features and in particular a good and detailed description of features concerning the transport network. Roads are categorized in 4 main operative classes; furthermore permanent trails adapted to haulage by mules (*mulattiera*) are reported.

Table 5. Transport network classification of the Carta d'Italia for military use

Class	Width m	Slope %	Other features
1	> 8	< 7; 7 - 12; > 12	Wall; bottlenecks and extra width
2	6 - 8	< 7; 7 - 12; > 12	Wall; bottlenecks and extra width
3	< 6	< 7; 7 - 12; > 12	Wall; bottlenecks and extra width
4	Not indicated	Not specified	Wall; bottlenecks and extra width
Mulattiera	Not indicated	Not specified	Not specified

A simple explanatory categorization of the road transportation network during the 1st WW in similar mountainous condition to the ones of Altopiano dei Sette Comuni is reported by Sigurtà (2002) which indicates *camionabili* as truck roads, generally with a width > 4.0 m and a gradient < 10% and the *carrozzabili* as road adapted for tractor with carriage, with a width between 2.50 and 4.0 m and a gradient < 10%. The same Author reports also the descriptions of the *mulattiera* which is characterized by a width variable between 1.5 to 2.5 m and a gradient higher than 10% (maximum 28-30%). Boglione (2008) reports that in mountainous area, the *camionabili* and *carrozzabili* roads can be characterized for short section also by a gradient higher than 10% (maximum of 12-14%). The digital images (.tiff) of the maps were obtained by scanning the maps. The scanned maps were thus aligned and georeferenced in WGS 84 UTM 32 N and then grouped in a single dataset.
In order to verify the condition of the forest road network at an intermediate state, historical aerial-photos of the Italian Aeronautic Group (GAI) dated 1954-55 (AA.VV., 2011) were collected and grouped in a single datataset. The GAI aerial-photos were scanned at 600 dpi resolution to be adapted to an application scale of 1:10000 (Savio, 2011).
The two dataset concerning the maps of the *Carta d'Italia* for military use and the GAI aerial-photos were therefore integrated in a single geodatabase (Figure 3).

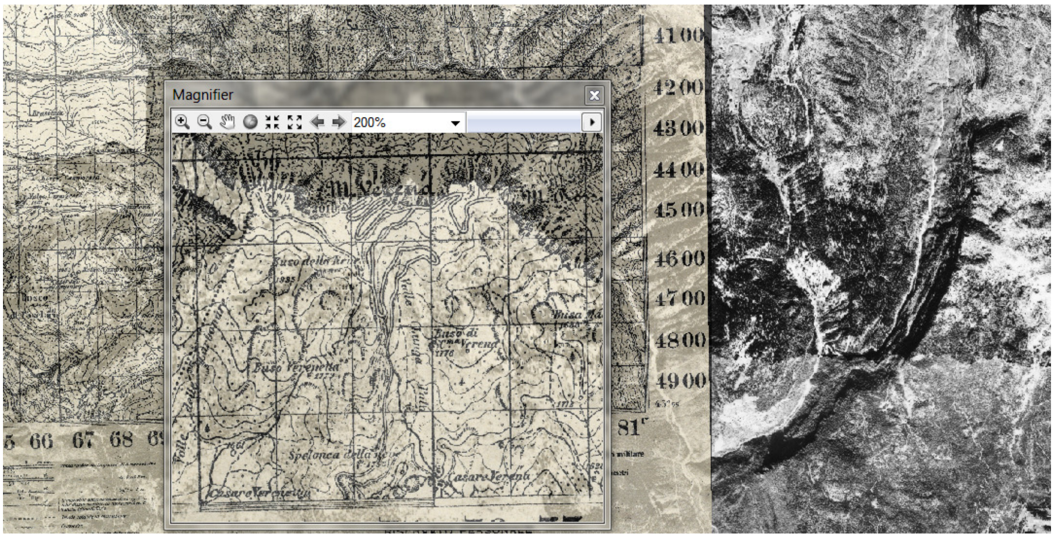

Figure 3. Historical source geodatabase with a map of the *Carta d'Italia* and GAI aerial-photos

3.3. Extraction of the historical transport network

The transport network on the 1917 historical maps was digitalized in vector format. For each transport network segment reported in the maps, the class, the width, the gradient and the presence of walls, bottlenecks and extra widths (as landings, switchback area and square) were reported.
On a first step the digitalization considered the same layout shown by the maps. Because the maps were not always reliable concerning the layout of the transport segments, a second step considered the alignment of the digitalized segment to the current road network previously surveyed by GPS.
The alignment considered integration of the information of the historical road network to the current road network. The integration was evaluated only where the segments in the maps clearly overlapped (within a buffer of 30 m) the segment surveyed by GPS. Where the historical road network was different, the road network was not integrated to the dataset of the current road network.
The forest road network shown in the GAI aerial-photos was digitalized and therefore integrated to the current road network. The final geodatabase of the current road network specified for each segment its existence in the three considered periods (1915-1918, 1953-1954, 2010-2011).

All the GIS operations, dataset management and analyses were supported by ArcGIS 10 (ESRI, 2010a), while the statistical analyses were sorted out by SPSS 18 (2010).

3.4. Field surveys plan

A part of the analysis attempted to survey current road segments overlapping the historical transportation network back to the 1st WW. The surveys were conducted by using a professional GPS with a resolution approximately to 1 m (Trimble Pathfinder ProXH).
The main investigated features were the deterioration of the artifacts (Figure 4) and the re-engineered condition of the historical transportation network (Figure 5).

Figure 4. Evaluation on the deterioration of retaining walls

Figure 5. A *mulattiera* partially re-engineered

The survey procedure considered to collect qualitative and quantitative features and parameters by a dedicated format developed in ArcPAD 8 (ESRI, 2010b).
The surveys were conducted in order to cover all the road classes included in the legend of the historical *Carta d'Italia*.
The survey plan was previously randomly extracted with the support of the GIS analysis. The field procedure considered the collection of different parameters and information within segments of 25 m length.
The following attributes were thus verified for each road segment:

- Width: the current average carriageway (m)
- Gradient: the current gradient (%)
- Current condition compared to the 1st WW one: completely re-engineered, partially re-engineered, partially preserved, completely preserved
- Historical artifacts: retaining walls, drainage systems (such as camber, culverts, ditches or cross drain) and bridges
- Historical artifact deterioration: high, medium, low, not valuable
- Road surface: current road surface (asphalt, gravel or natural)
- Current access: reporting the road traffic limitation and use

4. Results and Discussions

4.1 The road network from the 1st WW to nowadays

The data obtained from the digitalization of the historical maps of the 1st WW and from the digitalization of the GAI aerial-photos indicated a considerable increment (+126%) of the extension of the road network from the 1st WW to nowadays (Table 6).

Table 6. The road network extension between 1st WW to 2010-2011

Area	1st WW A km	1953-1954 B km	Δ AB %	2010-2011 C km	Δ BC %	Δ AC %
Verena	69.8	105.9	+51.7	155.4	+46.7	+122.6
Boscon	44.1	90.6	+105.5	102.2	+12.8	+131.7
Total	113.9	196.5	+72.5	257.6	+31.1	+126.2

The Class 3 and Class 4 road network of the 1st WW were included here as the legend of the *Carta d'Italia* detailed them useable for vehicles, while *mulattiera* was not considered in this calculation.
By comparing the road network extension (including forested and not forested area) between the 1st WW to the nowadays, the Verena area increased the road network density from 12.1 m ha^{-1} to 26.9 m ha^{-1}, while the Boscon area increased the road network from 13.1 m ha^{-1} to 30.3 m ha^{-1}.
Table 7 reports the current road network extension according to the operative level classification, whereas Table 8 shows the 1st WW road network extension according to the operative classification as indicated in the legend of the *Carta d'Italia*.

Table 7. Operative level of the current road network according to Table 3

Operative level	Boscon			Verena		
Class	km	%	m ha^{-1}	km	%	m ha^{-1}
1	7.3	7.1	2.2	12.8	8.2	2.2
2	42.1	41.2	12.5	26.2	16.9	4.5
3	31.0	30.4	9.2	67.2	43.3	11.6
4	21.8	21.4	6.5	49.2	31.7	8.5
Total	102.2	100	30.3	155.4	100	26.9

Table 8. Operative level of the 1st WW transport network according to Table 5

Operative level	Boscon			Verena		
Class	km	%	m ha^{-1}	km	%	m ha^{-1}
3	35.1	51.0	10.4	39.5	32.6	6.8
4	9.0	13.1	2.7	30.3	25.0	5.2
mulattiera	24.7	35.9	7.3	51.3	42.4	8.9
Total	68.8	100	20.4	121.1	100	21.0

4.2 The original alignment of the 1st WW transport network

As detailed in Table 8, the 1st WW road network in the study areas was composed by Class 3, Class 4 and *mulattiera*. According to the legend of the *Carta d'Italia*, it is evident that the roads were characterized generally by a width smaller than 6 m (including shoulders and carriageway) and the *mulattiera* was a considerable part of the 1st WW transportation network. This condition may be reasonable comparable to the condition of the military road network in mountain areas described by Boglione (2008) in the North-western part of Italy and by Sigurtà (2002) in the North-central part of Italy.
The analysis verified the location of the transportation network according to the terrain characteristic surrounding each transport segments (a buffer of 50 m was considered for both the side of the road segment). The analysis considered the terrain steepness (or terrain gradient) in percentage. The terrain gradient was calculated by a Digital Terrain Model with a resolution of 10 m x 10 m. At this resolution the morphology of the terrain was considered constant between the 1st WW and nowadays situation. Based on this approach, the results highlighted that in the Verena area the 1st WW transportation network (135 segments with an average steepness of the surrounding terrain of 30.95%) was located in terrain steeper than in the Boscon area (102 segments with an average steepness of the surrounding terrain of 22.17%). The two means was thus compared by the non-parametric test of Mann-Whitney with the null hypothesis that the two means were equal. The result reported a ρ-value = 0.000 justifying the rejection of the null hypothesis. Therefore a total of 214 segments were extracted and analyzed in term of gradient. The gradient was determined by considering the rise between the start and the end vertex of each segment and the length of the same segment. The procedure was based on a semiautomatic method developed in ArcGIS 10. Data obtained on the gradient of each transportation network segment highlighted an average gradient of 5.93% for the Boscon area and of 8.62% for the Verena area. The Independent-Samples T Test procedure was applied to test the significance of the difference between the two means with a confidence interval of 95%. The T-test reported a ρ-value = 0.000, justifying the rejection of the null hypothesis that the two means were equal.
Next the One-Way ANOVA procedure let to compare the means of the gradient for the three groups: Class 3, Class 4 and *mulattiera*. As the Levene statistic test confirmed the null hypothesis that the group variances were equal, the pairwise multiple comparisons was based on the Least Significant Difference (LSD) test. The highlights of the statistical analysis are reported on Table 9.

Table 9. LSD test on the means of the gradient for the three historical transportation classes (*the mean difference is significant at the 0.05 level)

Transportation class A	Transportation class B	Mean difference (A-B)	Std.error	*p-value*	Confidence interval 95% Lower bound	Confidence interval 95% Upper bound
Class 3	Class 4	-0.965	0.987	0.329	-2.91	0.98
	*mulattiera**	-4.259	0.812	0.000	-5.86	-2.66
Class 4	Class 3	0.965	0.987	0.329	-0.98	2.91
	*mulattiera**	-3.294	1.013	0.001	-5.29	-1.30
mulattiera	Class 3*	4.259	0.812	0.000	2.66	5.86
	Class 4*	3.294	1.013	0.001	1.30	5.29

It can be observed that the *mulattiera* was the element of the 1st WW transportation network with the higher gradient, in average 10.0% with a maximum value of 23.8%. The road segments included in the Class 3 and Class 4 showed an average gradient of 5.75% and 6.72% with a maximum value of 18.8%.

4.3 The current alignment of the 1st WW transport network still in use

The length of the current road network overlapping the 1st WW transportation network was evaluated 80.5 km, approximately the 31.3% of the existing road network. Therefore the current alignment of the 1st WW transport network still in use as forest road network was analyzed in term of carriageways and gradient (Table 10) by considering the data collected by GPS during 2010 and 2011.

The analyzed road network was composed of 87 segments grouped according to their origin reported in the *Carta d'Italia*. The resulting means for the carriageways and the gradient are reported on Table 11.

Table 10. Extension of the 1st WW transport network still in use as forest road network

Operative level	**Verena**			**Boscon**		
Class	**km**	**%**	**m ha^{-1}**	**km**	**%**	**m ha^{-1}**
3	25.4	62.1	7.5	19.5	49.0	3.4
4	6.3	15.5	1.9	16.3	41.2	2.8
mulattiera	9.1	22.4	2.7	3.9	9.8	0.7
Total	40.8	100	12.1	39.7	100	6.9

Table 11. Descriptive statistic for the carriageway and gradient of the 1st WW transport network still in use as forest road network

Variable	**Group**	**n°**	**Mean**	**Std.Dev.**	**Std.Error**	**Confidence interval 95%**		**Min.**	**Max.**
						Lower bound	**Lower bound**		
CW (m)	Class 3	46	3.6	0.660	0.097	3.4	3.8	2.5	5.0
	Class 4	22	2.8	0.527	0.112	2.6	3.0	2.0	4.0
	mulattiera	19	3.1	0.762	0.175	2.7	3.4	2.0	4.0
	all	87	3.3	0.746	0.080	3.1	3.5	2.0	5.0
VG (%)	Class 3	46	4.3	3.300	0.487	3.3	5.3	0.0	10.3
	Class 4	22	5.2	3.540	0.755	3.6	6.8	0.0	10.3
	mulattiera	19	6.6	5.450	1.250	4.0	9.2	0.0	16.2
	all	87	5.0	3.974	0.426	4.2	5.9	0.0	16.2

The One-Way ANOVA was used to compare the means of the carriageway and the gradient between the three groups Class 3, Class 4 and *mulattiera*. The pairwise multiple comparisons was based on the Least Significant Difference (LSD) test for the evaluation of the means of carriageway, as the Levene statistic test confirmed the null hypothesis that the variances of the three group were equal (Table 12). For the gradient the Levene statistic test did not confirms the null hypothesis that the group variances were equal and for this reason the Tamhane T2 test was applied (Table 13).

Table 12. LSD test on the means of the carriageway (CW) (*: the mean difference is significant at the 0.05 level)

Group (Class)		**Mean difference**	**Std.error**	***p-value***	**Confidence interval 95%**	
A	**B**	**(A-B)**			**Lower bound**	**Upper bound**
Class 3	Class 4*	0.842	0.170	0.000	0.504	1.179
	*mulattiera**	0.584	0.178	0.002	0.230	0.939
Class 4	Class 3*	-0.842	0.170	0.000	-1.179	-0.504
	mulattiera	-0.257	0.205	0.213	-0.664	0.150
mulattiera	Class 3*	-0.584	0.178	0.002	-0.939	-0.230
	Class 4	0.257	0.205	0.213	-0.150	0.664

Table 13. Tamhane T2 test on the means of the carriageway (CW) (*: the mean difference is significant at the 0.05 level)

Group (Class) A	B	Mean difference (A-B)	Std.error	*p-value*	Confidence interval 95% Lower bound	Upper bound
Class 3	Class 4	-0.875	0.898	0.707	-3.115	1.366
	mulattiera	-2.270	1.342	0.280	-5.717	1.177
Class 4	Class 3	0.875	0.898	0.707	-1.366	3.115
	mulattiera	-1.395	1.461	0.722	-5.088	2.297
mulattiera	Class 3	2.270	1.342	0.280	-1.177	5.717
	Class 4	1.395	1.461	0.722	-2.297	5.088

As it can be seen from Table 12, the Class 3 reported a significantly larger carriageways than Class 4 and *mulattiera*; alternatively the statistical analysis indicated that the means of the carriageways of Class 4 and *mulattiera* are equal.
As it is indicated on Table 13, the means of the gradient of all the groups are equal. For what it concerns the *mulattiera*, it could suggested that only the *mulattiera* that have been re-designed with a gradient suitable to the traffic of vehicles are nowadays part of the road networks.

4.4 Evaluation on the remaining artifacts of the historical transportation network

The evaluation of the current state of the 1st WW transportation network was determined through a survey of 145 control points along the current road network. The 36% of the control points was collected on roads originally 1st WW Class 3, 48% on roads 1st WW Class 4 and the remaining 16% on *mulattiera*.
The results highlight (Table 14) that a great number of road segments originally classified as Class 3 are currently adapted to vehicles with low mobility and high load capacity (corresponding to the Class 1 and Class 2 in the current operational classification reported on Table 3). The results also highlight as the *mulattiera* has been often re-engineered to the current operational Class 2 and Class 3, while the road segment originally classified as Class 4 have been adapted to an high mobility and medium low load capacity or to an high mobility and a low or null load capacity (corresponding to the Class 3 and Class 4 in the current operational classification reported on Table 3).

Table 14. Current operational classification of the 1st WW transportation network

1st WW operational classification *(see Table 4)*	Current operational classification *(see Table 3)* Class 1	Class 2	Class 3	Class 4
Class 3	7.7%	55.8%	32.7%	3.8%
Class 4	-	10.0%	67.1%	22.9%
mulattiera	-	56.5%	43.5%	-

As shown in Figure 3, *mulattiera* have been substantially completely re-engineered in their horizontal and gradient alignment. The degradation of the historical artifacts, when they could be still valuated, was appreciable high for the *mulattiera* and for the Class 3 (Figure 4).

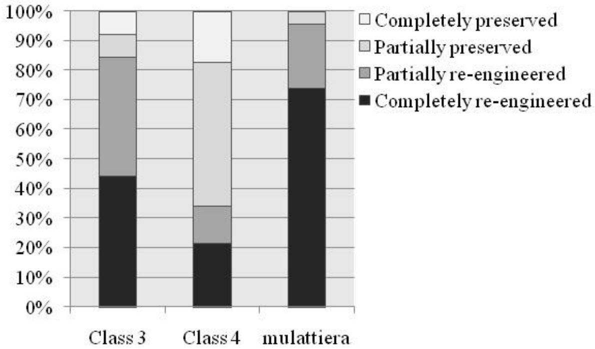

Figure 3. Upgrading of the historical transportation network according to the transportation classes reported in the *Carta d'Italia*

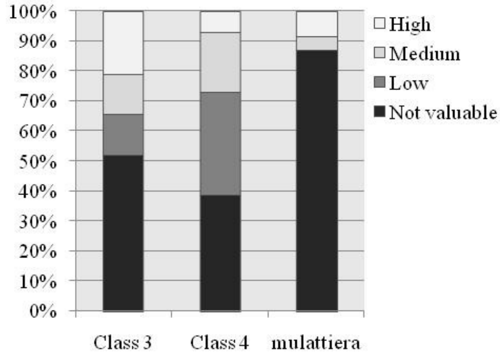

Figure 4. Deterioration of the alignment and artifacts of the 1st WW transportation network

Furthermore the current roads closed to the ordinary traffic (forest roads) are the most preserved in term of the original alignment and artifacts, while the current roads opened to the ordinary traffic (public roads) are the most upgraded and re-engineered in respect to their origin (Figure 5). For both the group it seem that barely the 50% of the artifacts shows a high or medium deterioration.

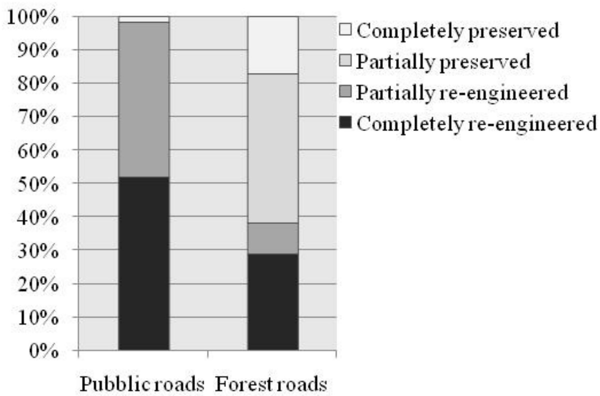

Figure 5. Upgrading of the 1st WW transportation network according to current traffic limitation

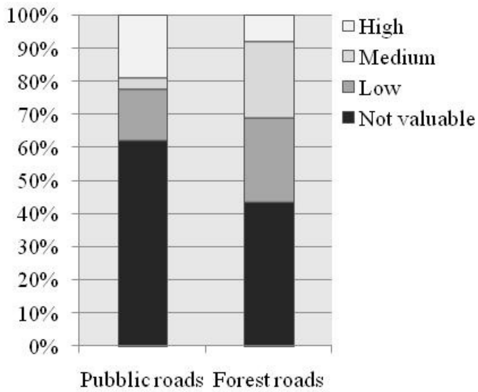

Figure 6. Deterioration of the alignment and artifacts in relation to the traffic limitation

5. Conclusions

The purpose of this study was to investigate the improvement of the transport network from the beginning of the 1st WW to the existing road network within mountainous forest areas.

The first results for the two areas selected in the Altopiano di Asiago confirmed that an appreciable part of the original 1st WW transportation network is still in use. Part of the network has been totally re-engineered in order to support an ordinary traffic related to agriculture and forest activities and nowadays also for the summer and winter recreational activities. Part of the network has been remained partially preserved because only used for forestry or stone extraction purposes.

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Determination of the forest road network influence on the supply chain for firewood production by discrete Event simulation

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1. Introduction

Simulation is the process of building a model of a real or proposed system to study the performance of the system under specific conditions. A simulation model could be classified as being static or dynamic, deterministic or stochastic and discrete or continuous [Bank et al. 2005].
In the last decade, in several studies concerning forest operations, dynamic, stochastic and discrete simulation has been applied [Asikainen 1998; Wang and LeDoux 2003; Väätäinen 2010; Asikainen et al. 2010; Hogg et al. 2010]. Dynamic because the effects of changing variables and the workflow of the system according to the simulation time are analyzed, stochastic because randomness of observation is considered; discrete because the state variable changes only at a discrete set of point in time. This type of simulations is generally called discrete event simulations [D-es] and it is generally applied to analyze the behavior of a system defined as a collection of entities, usually workers and machines, that act and interact toward the accomplishment of some logical end over time [Law and Kelton 1991].
Asikainen [1995] and Ziesak et al. [2003] report some advantages of the D-es simulation techniques , one of which is the capability of this application to analyze discrete and complex real-world situations that cannot be solved by analytical operational methods because of various interactions between the system components. In addition the approach of D-es lets to describe the interactions between the system elements and to model the effects of random processes.
At tactical level, many D-es models were developed for the analysis of the efficiency in the transport interactions. The logistic of a chipping terminal was also modeled by a D-es model, which was based on a manufacturing simulator in order to compare different loading and transport technologies [Asikainen 1998]. In this study chipping into truck, chipping onto ground and loading using a wheeled loader, long-distance transport by truck with drawbar trailer, by truck with semitrailer and by truck with interchangeable platforms were considered.
Väätäinen [2010] investigated through D-es the cost-effective patterns of harwarders for forest machine contractors in different logging structures and conditions. A D-es model was also programmed to find optimal set-ups for the supply chain of crushed material made from stumps at different road transport distances. The simulation model was based on the continuous supply of crushed material from landings to a district heating plant [Asikainen 2010]. Recently, a D-es model was developed to find the optimal set-ups for the timber yarding-processing-truck transport system in mountainous condition using a logging site and transport distance database as input [Asikainen et al. 2010].
At operational level applications of D-es model concern also the analysis of interaction for studying the cost-efficiency of single machine or specific operation systems. By changing simulation inputs and observing the results outputs, machine and system behaviors can be studied and compared with different simulation runs. This allows largely deterministic base simulations that can be carried out to illustrate the effects of machine interactions. Also a ground-based timber harvesting system was modeled by an object-oriented model from felling to extraction in order to evaluate the interaction of stands, harvester treatments, machines and extraction patterns [Wang and LeDoux 2003].
Chipping operation systems in thinning were also analyzed by evaluating bin size, chipper productivity, in-field extraction distance and forest-road haulage distance [Talbot and Suadicani 2005], while multi-stem mechanized

harvesting operation was analyzed under South Africa condition by comparing the current system to two hypothetical systems. One of the alternative systems was based on modifying the operation procedures but by considering the same machines and equipments of the current system, the second one on changing also the machine and the equipments [Hogg et al. 2010].

Some of these works have addressed the development of D-es on a single component of a more complex supply chain [Asikainen 1998; Wang and LeDoux 2003; Talbot and Suadicani 2005; Hogg et al. 2010] and only few have analyzed the interaction between more parts on a complex supply chain [Asikainen 2010; Asikainen et al. 2010].

The study aims to develop a D-es model for evaluating the productivity of the wood supply chain for firewood production according to the current operational level from the harvesting site to the firewood production terminal. Therefore the D-es model will be applied to evaluate the productivity of the entire supply chain by considering the complexity of the transportation network with the support of the GIS network analysis according to different scenarios.

2. Materials and methods

2.1 Study site

The study concerns a firewood supply chain located in the in northeastern part of Italy (Cansiglio forest), latitude N 46°12'37 – 46°11'67, longitude E 12°45'03 – 12°46'61.

The forest plot (11.4 ha) consisted in a high stand forest almost exclusively of beech (*Fagus sylvatica L.*) and sporadic individuals of Norway spruce (*Picea abies Karst.*). The altitude ranged from 1248 m to 1398 m a.s.l. with a slope gradient ranging between 5 and 35%. The average growing stock was 423 m^3 ha^{-1} with a mean rate of growth equal to 7.6 m^3 ha^{-1}. The adopted silvicultural system was the shelterwood method and the analyzed operation regards a shelterwood selection cut with a cut mass of 776 m^3 on 11.4 ha (exploitation percent about 15%). The mean diameter at breast height of the cut trees was 24 cm and the average height was 22 m.

2.2 Study layout

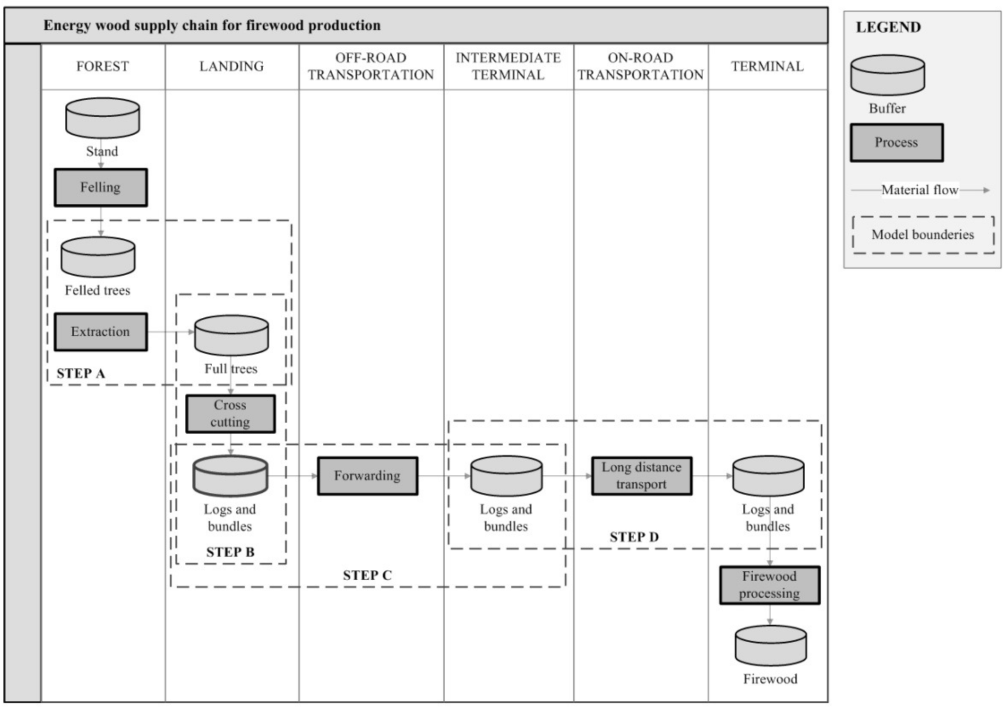

Figure 1. Supply chain of full trees for firewood production.

The study evaluates a distinctive supply chain for firewood production. The case study can be considered a representative situation of the application of the full tree system (FTS) for firewood production from broadleaves high stands in medium gentle terrain. The supply chain was identified by four steps (Fig. 1): extraction (Step A), cross-cut operation (Step B), off-road transport (Step C) and on road transport (Step D).

The study considers the processes and the workflow of the wood from the stump site to the terminal where wood in form of logs and bundles of 1.1 m length assortments were cut and split into firewood.

The extraction (Step A) was performed by hauling the felled full trees from the stump to the nearest landings. The extraction operation was ground based and involved one agricultural tractor (67 kW) with a forest winch. This operation was performed by two operators, one driving the tractor and one preparing and hooking the loads (normally one full tree).

At the landing four operators cross-cut full trees into logs (4-6 m length and > 20 cm diameter) and into small assortments of 1.1 m length considering three different classes of diameter at half length (< 10 cm, 10-15 cm, 15-20 cm) (Step B). One operator was involved in the piling operation of logs by using a loader (lifting moment 60 kN m and maximum reach of the boom 6.50 m) attached to a agricultural tractor (74 kW), which was located in front of the cross-cutting area. When full trees arrived to the landing, the same operator grappled and moved the unhooked load into the cross-cutting area (landing). At the same time the tractor with the forest winch went back to stump area for a new extraction cycle. The same operator on the tractor with the crane pilled logs and bundles in piles (maximum 4-4.5 m height), which were located at the right and left side of the same tractor. Other two operators cross-cut the full trees while the remaining operator was mainly busy to sort, according to the diameters at half length (< 10 cm, 10-15 cm, > 15 cm), the small assortments into three different frames (one for each diameter) which were then used for assembling the bundles (70 cm diameter).

Logs and bundles were subsequently transported off-roads to the transshipment site along tractor roads by an agricultural tractor (81 kW) with a trailer with mechanical traction and a payload of 11 t (Step C). Transport on public road to terminal was performed by a 4x2 WD truck (294 kW) and trailer with a total payload of 22 t (Step D).

2.3. Definition of the D-es model

The model was developed on the base of Figure 1 to meet the primary objective to evaluate the influence of the extension of a forest road network on the firewood supply chain. The model was developed as a dynamic, stochastic and discrete simulation model (D-es).

The D-es model was created using the Witness simulation modeling software [LANNER 2009], a visual entities-based simulation application for system dynamics models.

The model was therefore constructed interactively in three steps (definition step, detailing step and logic step) via graphics interfaces. According to the workflow of the supply chain, the names and quantities of the elements and the variables of the system were specified at the definition step. The detailing step allowed then to define the parameters of each element such as cycle times, setup times, transport capacities and delay times. The logic step determined then how each element operates and how its operation depends on the action of other elements or state variables.

2.4. Functions and parameters of the D-es model

Simulation calls for information about the variables and processes. For instance, production functions for the different working phases of the supply chain needs to be defined. To define the productivity for extraction, cross-cut operation, off-road transportation and on-road transportation time studies were sorted out on May and June 2009 and according to the basic time concepts proposed by Björheden (1991).

Extraction was studied adopting the stop-watch method. Data collection of the main factors affecting time consumption of extraction considered: volume (generally a single tree, V, m^3), loaded (LD, m) and unloaded driving (UD, m) distance and slope gradient (SL, %) of the trail. The load volume (V) was determined after the cross-cut process by measuring the diameter at half length and the length of each single log (log volume, LV) and by recording the number and the size of each small assortment (small assortment volume, SAV) according with the frame where they were sorted. The extraction distances and the slope gradients were measured by a laser rangefinder with an integrated compass allowing to measure straight distance and slope within 400 m. The cross-cut operation of full tree at landing was studied with the support of a digital video-camera and the work sampling method. The off-road and on-road transportation was also investigated by adopting the stop-watch method to determine the average speed for loaded and empty travel and for loading and unloading time. In the case of the on-road transportation the distance was always the same.

2.5. Statistical analysis

The time and motion study of the ground-based extraction was subdivided in travel loaded TL and in travel unloaded TU. For the travel loaded the productivity hypothesis was TL = f (V, LD, SL) and for the travel unloaded TU = f (UD, SL). The time and motion study of the cross-cut (CC) supposed the following productivity hypothesis CC = f (V, V_Type), where V_type corresponds to a factor equal to 1 in the case of a rate of small assortment higher than 10% on the total volume, otherwise the factor is 0.

According to Stampfer et al. [2010], the variance analysis was used to quantify the influence of nominal and ordinal-scaled variables. Also the analyses for the three time and motion studies consisted in: estimation of significant effects of the co-variables and factors and analysis of their significance, the evaluation of the non-linearity of the co-variable, analysis of the interaction between factors and co-variables, parameters estimation of significant factors and co-variables and regression analysis. Further, the Box-Cox transformations procedure was applied to determine an optimal transformation of the tree volume for stabilizing the variance and making the deviations around the model more normally distributed.

The locking and unlocking time for each cycle time was verified in terms of distribution. The distributions were analyzed by the Kolmogorov-Smirnov test (K-S) at the confidence interval of 0.05 and supposed to be of the normal type.

Also for the collected data concerning the speeds of the off-road transportation and the on-road transportation and the un-loading and loading time were analyzed by the K-S test at the confidence interval of 0.05 and supposed to be of the normal type.

Randomly-occurring delays have an important influence on machine and operation performance. The frequency of the time between breakdowns and the breakdown times were also determined. The distributions of breakdown time and interval were studied by the K-S test. All the breakdown distributions were supposed to be of the Erlang type with shape factor k equal to 2 (bell-shaped distribution, strongly skewed to the left and with a shape similar to lognormal distribution) [LANNER 2009].

2.6 Model validation

The D-es model was built according to the investigated situation. During the model construction the logical proceeding of work sequences were tested by running the model step by step and observing the interaction between all the elements by graphic and value outputs.

According to Banks et al. [2005], the validation ensures that the model is a realistic representation of the real system. The simulation model was verified with 15 daily firewood loads unloaded at the terminal, which were registered by the forest enterprise. The validation supposed the daily average (5 working days, 2880 min) of unloaded firewood mass in term of logs and small assortments of 15 repetitions with a warm-up period of 480 min and several different sets of random number streams.

2.7 Experimental design

The experiment design considered 8 different extensions (scenarios, SC) (Tab. 1) of the transportation network as a result of the increasing number of landings within the forest plot (Fig. 2).

Table 1. Scenarios (SC) and main values of the transportation network according to the increment of the forest landings.

	Site	EXTRACTION NETWORK			Site	FOREST ROAD NETWORK			PUBBLIC ROAD NETWORK	
		distance				density	distance		distance	
SC	Landing	Mean	StDev	Sum	Transshipment	Density	Mean	Sum	Mean	Sum
-	n.	m	m	km	n.	m ha^{-1}	m	km	km	km
A	1	230	146	336	1	7.73	750	137	31.20	1981
B*	2	116	60	169	2	14.48	968	177	31.85	2022
C	3	79	36	116	2	26.14	1112	203	32.11	2038
D	4	68	30	99	2	38.44	1254	229	31.92	2026
E	5	65	30	95	2	38.44	1277	233	31.59	2005
F	6	61	30	89	2	56.92	1314	240	31.55	2003
G	7	58	29	84	2	68.16	1263	230	31.73	2014
H	8	53	26	77	2	68.16	1238	226	31.66	2009

* current situation

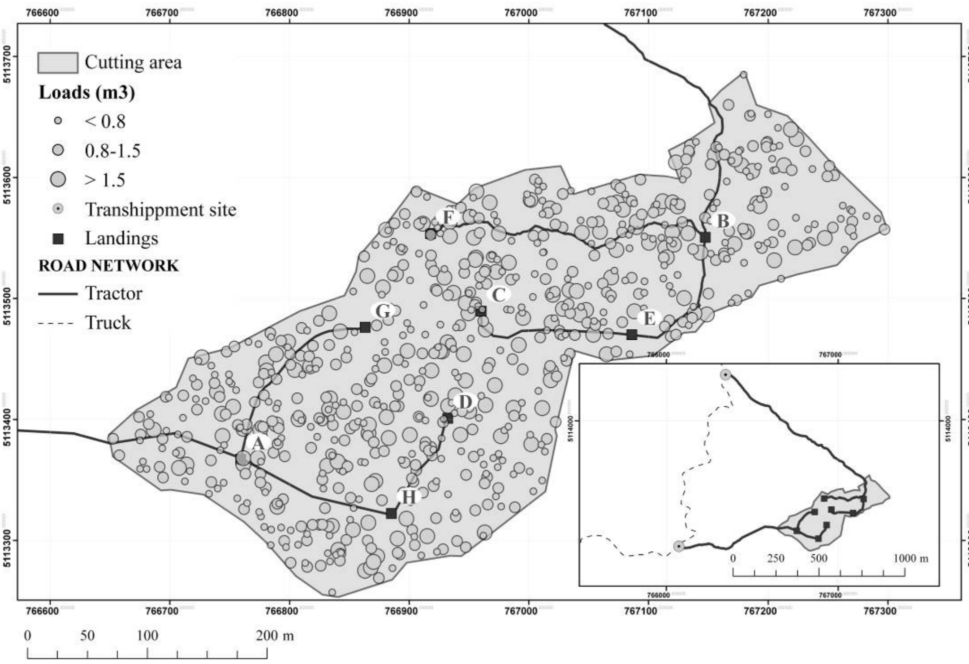

Figure 2. Layout of the studied area with the distribution of the loads, the maximum supposed road network extension and the landings location.

The numbers of the loads (the felled trees) corresponds to the location of the 731 stump sites inside the study area. As the precise location of the all the stump sites was not fixed, the spatial distribution of the load was determined by the *Generating random points tool* of ArcGIS 9.3–ArcInfo which randomly places a specified number of points within an identified area [ESRI 2009].

As a consequence the volume of each load was determined by random number generation function according to the distribution resulting by the 105 loads, which were observed during the time and motion study.

For each scenario, a routing analysis was thus carried out to determine the total transportation distance covered by extraction, off-road and on road transportation to supply all the harvested wood (logs and bundles) to the final terminal. All the routes connecting each loads to landings and also the landings to the transshipments sites and the transshipments

sites to the terminal were calculated by ArcGIS network analysis [ESRI 2009] according to Djikstra's algorithm, which is implemented for determining multiple origin-multiple destination or multiple closest facilities [Cavalli and Grigolato 2010].
The network analysis supported thus the definition of the input parameters about the transportation distance for each load according to the 8 scenarios.
Once all the parameters were defined, D-es simulation was launched to perform 15 repetitions for each scenario with a warm-up period of 480 min and several different sets of random number streams.
On the present work, all the statistical analyses were sorted out using SPSS statistic software [SPSS 2009].

3. Results

3.1 Simulation model parameters

Table 2 shows the results about the regression models and the distributions and the basic parameters used in the model for the simulations.

Table 2. Elements and parameters of the D-es model.

Step	Description	Unit	Function/Distribution type	Obs.	*p*-value
A	Unhooking (PSH_0)	s/100	Normal (μ = 46.93 SD= 23.6)	105	0.710 (K-S)
	Hooking (PSH_0)	s/100	Normal (μ = 327.3 SD= 114)	105	0.471 (K-S)
	Travel Unloaded TU (PSH_0)	s/100	TU = 33.683+(0.963×D) + 2.612×SL (R^2 = 0.72)	105	0.000 (reg)
	Travel Loaded TL (PSH_0)	s/100	TL = –27.379+(142.713×$V^{0.38}$)+(1.003×DL) (R^2 = 0.51)	105	0.002 (reg)
	Delays time	min/100	Erlang (μ = 6.115 SD= 4.769)	21	0.083 (K-S)
	Interval delay time	min/100	Erlang (μ = 27.58 SD= 7.38)	21	0.172 (K-S)
	V	m^3	Normal (μ == 1.046 SD= 0.503)	105	0.732 (K-S)
B	Cross-cut (PSH_0)	min/100	CC=0.558+(11.084×$V^{0.26}$)-(3.068×V_TYPE) (R^2 = 0.61)	53	0.006 (reg)
	Delay	min/100	Erlang (μ = 2.111 SD= 1.278)	19	0.061(K-S)
	Interval delay time	min/100	Erlang (μ = 33.211 SD= 5.183)	19	0.185 (K-S)
C	Loading	min/100	Normal (μ == 8.859 SD= 0.765)	14	0.341 (K-S)
	Travel loaded	km h^{-1}	Normal (μ == 6.371 SD= 0.269)	14	0.201(K-S)
	Unloading	min/100	Normal (μ == 9.482 SD= 1.004)	14	0.239 (K-S)
	Travel empty	km h^{-1}	Normal (μ == 7.10 SD= 0.368)	14	0.097 (K-S)
D	Loading	min/100	Normal (μ == 15.93 SD= 0.975)	8	0.058 (K-S)
	Travel loaded	km h^{-1}	Normal (μ == 34.6 SD= 2.115)	8	0.067 (K-S)
	Unloading	min/100	Normal (μ == 18.71 SD= 1.176)	8	0.163 (K-S)
	Travel empty	km h^{-1}	Normal (μ == 35.7 SD= 2.016)	8	0.066 (K-S)

PSH_0 = Productive system time without delays

The productivity resulting from the composed extraction model, including the regression model of the travel unloaded (TU) and the travel loaded (TL) and the distribution of the hooking and unhooking operations, is reported on Figure 3. This composed model concerning the Step A highlights the effects of the volume and the extraction distance on the effective productivity (calculated on the Productive System Hour without delays - PSH_0) (m^3h^{-1}) of the extraction system.
Figure 4 reports the results (m^3h^{-1}, PSH_0) of the regression model of the cut-crossing operation at landing according to the rate of small assortment resulting from the operation respect to the total volume of the load.

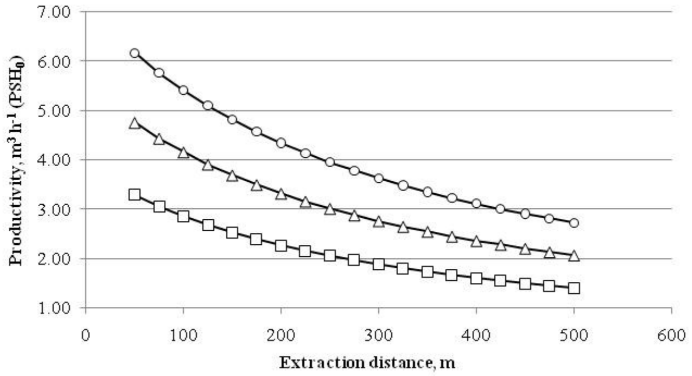

Figure 3. Extraction productivity for an average slope of 14% and three extracted volume: 1.0 m^3 (-□-), 1.5 m^3 (-Δ-) and 2.0 m^3 (-○-) .

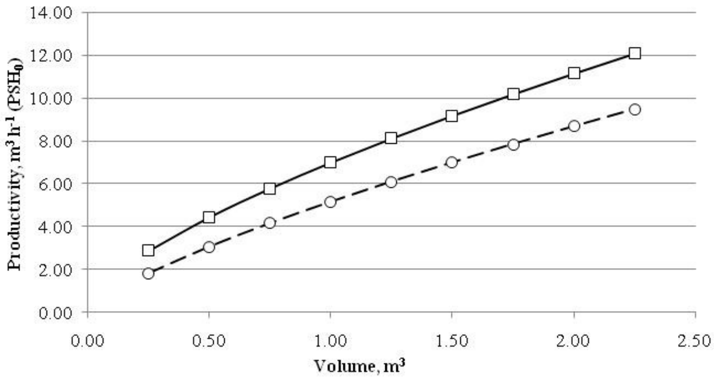

Figure 4. Cross-cut productivity with a rate of small assortment higher than 10% (-○-) and lower than 10% (-□-).

3.2 Influence of the road network extension on the transportation system productivity

The average output equal to 1.48 truck and trailer per day to the terminal of the 15 replications reported by the D-es model built according to the current state (corresponding to the Scenario B) was considered consistent to the real condition reporting an average of 1.52 truck and trailer per day to the terminal. For this reason the model has been considered reliable and hence it was used for the proposed aims.

The influence of the increment of the forest road density and the extracted volume on the productivity was evaluated by the variance analysis and then by the linear regression analysis. The analysis of the variance reported that the extracted volume does not have a significant effect (*p*-value 0.067) on the productivity of the supply chain, hence the forest road density (DN) was assumed as the main variable influencing the productivity (*p*-value 0.001). For this reason a curve estimation procedure lets to estimate a significant (*p*-value 0.000) regression model at confidence level of 95%. (Tab. 3) to fit the outputs resulting from the 8 Scenarios (Fig. 5).

Table 3. Regression model and parameters on the hour productivity (m^3 h^{-1}) at terminal

Parameters	Estimation	SD	Statistic, t	P-value
Intercept	22.7773	0.196801	115.738	0.0000
DN Forest road density	-37.8646	3.50748	-10.7954	0.0000
REGRESSION MODEL	Productivity = $(22.7773-37.8646\times DN^{-1})^{0.5}$			

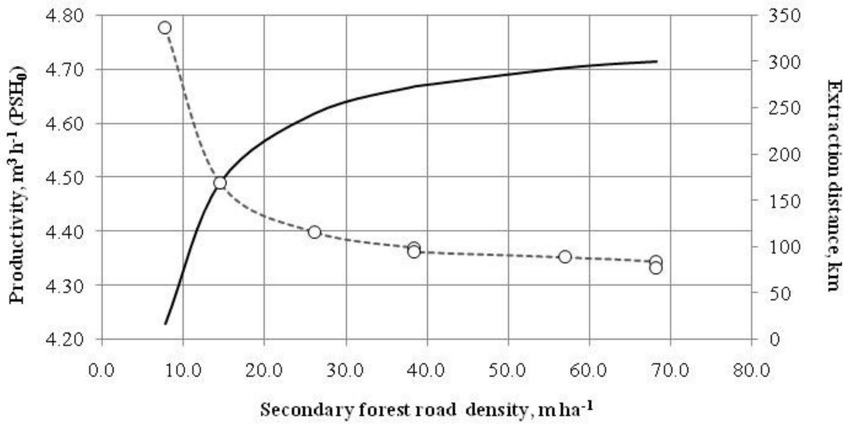

Figure 5. Influence of the density of the forest road density on the productivity (—) of the supply chain of wood for firewood production and the corresponding total traveled extraction distance (--○--).

From Figure 5 it appears that the increment of the secondary forest road density up to 25-30 m ha^{-1} could be considered a significant feature to increase the productivity of the supply chain. As can be seen, the current forest road density (Scenario B) is 14.48 m ha^{-1}. An increment of the current forest road extension to 20.00 m ha^{-1} (+38%, corresponding to 62 m in 11.4 ha) could correspond to a slightly increment of the productivity up to 1.8-2.0%. Therefore by the same supposed increment of the forest road network, the sum of the extraction distance (travel unloaded and travel loaded) would decrease for the entire operation of about 18-20%, corresponding to a reduction of 30-34 km covered distance.
It should, however, be noted that the curve reported in Figure 5 highlights a slightly positive influence when DN increase over 20-22 m ha^{-1}.

4. Discussion and conclusion

Simulation is the process of building a model of a real or proposed system to study the performance of its performance under specific conditions. The analysis of forest operations and wood supply chains has recently been applied in order to analyze discrete and complex real-world situations that could not be solved by analytical operational methods.
The study has presented a first approach of a D-es model integrated with a GIS network analysis to evaluate the influence of the interaction between three main transportation systems occurring during forest operations (extraction, off-road and on-road transportation) on the final productivity of a wood supply chain.
The results indicate that the increment of the forest road network may significantly increase the productivity of the wood supply chain. For the specific investigated condition, the increment of the forest road network showed only a slight increment on the productivity (up to 2%). Presumably this correlation depends on the characteristics of the investigated supply chain, which considered a harvesting site characterized by even terrain with an average slope gradient approximately equal to 18%.
According to the general indication reported by Baldini et al. [2008] the current forest road density, evaluated in 14.48 m ha^{-1} and corresponding to Scenario B, could be considered a low index for a productive forest. Therefore the increment to 20-22 m ha^{-1} could be considered reasonable by taking into account that in average in Italy the forest road network is approximately about 18 m ha^{-1} and by considering that in even terrain with a slope gradient of 40% (higher than the investigated area) forest road density can be approximately to 25-30 m ha^{-1} [Hippoliti 2004].
The proposed study highlighted the possibility to integrate the D-es approach to the GIS analysis to support the complex evaluation of the wood supply chains from the stump site to the final processing terminal.
The main limitation of this study was due to the fact that the investigated area represented an operative condition located in medium gentle terrain. Future work should include the analysis of forest productive sites in steep terrain where the forest road density is more complex to evaluate and the extraction transportation network is mainly based on cable systems.

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SUMMARY

In this study a Discrete-event simulation (D-es) has been developed to analyze the wood supply chain for firewood production in a mountain area in the North-eastern Italy. The D-es is applied in the modeling of extraction (Full Tree System), processing of roundwood into wood assortments (cross-cut and sorting), off-road and on-road transport.

In order to estimate the productivity functions and parameters, field studies were conducted to gather data about the different operations linked in the model. Also a GIS network analysis was developed to integrate the spatial information on covered distance to the D-es model for each of the supposed Scenarios.

The results indicates that an increment of 5 m ha^{-1} of the forest road network could significantly increase the productivity of the wood supply chain up to 2%.

Keywords: forest operation, supply chain, firewood, Discrete-event simulation

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A strategy for management of abandoned mountain pasture land colonized by dwarf pine

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Abstract: *Uncontrolled development of natural afforested areas might represent a problem by itself, often implying loss of cultural landscapes and habitat variety, bio and eco-diversity depletion, territorial homogenization with loss of economic and natural resources. In the northern part of the Altopiano dei Sette Comuni, a plateau area in the Venetian Alps, dwarf pine (Pinus mugo Turra) has been the most invasive specie, with an high impact in the occupation of alpine pasture land, road, paths and historical sites.*
The analysis considers the operative costs for both felling transport and chipping of dwarf pine stems to intermediate landings. The logistic problem has been widely analyzed by a GIS based decision support system based on network analysis model and assuming various scenarios considering different levels of upgrade of the forest road network. Supply-cost curves have been then constructed to analyze the total reclamation cost in terms of quantities of wood material.
The study highlights that the operative costs for harvesting wood material are high. The supply-cost actually ranges from 52 € t^{-1} to 143 € t^{-1} and it decreases, ranging from 52 € t^{-1} to 107 € t^{-1}, only if the upgrade of the forest road network is concerned.
The work highlights how the financial measures adopted by European Union, as well as by national and regional governments seems to be not sufficient to counteract the phenomenon.
The opportunities for an alternative use of the material in a small-scale process, in order to overcome the economic constraints, are considered.

Key words: Woodchips; Forest road network; GIS; dwarf pine
Parole chiave: Cippato; Viabilità forestale; GIS; Pino mugo

1. Introduction

Low-intensity agricultural practices, such as grazing, play a significant role for nature conservation in Europe. Many nature-like areas are in fact the product of some human influence and the conservation of these areas depends entirely on the continuation of this influence (OSTERMANN, 1998).
The European Landscape Convention actually defines the landscape as "*an area, as perceived by people, whose character is the results of the action and interaction of natural and/or human factors*" (COUNCIL OF EUROPE, 2000), so that landscape protection implies "*actions to conserve and maintain the significant or characteristic features of a landscape, justified by its heritage value derived from its natural configuration and/or from human activity*".
Even the Council Directive 92/43/EEC "*on the conservation of natural habitats and of wild fauna and flora*" (Habitat Directive) highlights that natural habitats are "*terrestrial or aquatic areas distinguished by geographic, abiotic and biotic features, whether entirely natural or semi-natural*" which means that "*natural*" habitats also include "*semi-natural*" areas, created and maintained by human activities, such as pastures.
Nowadays the uncontrolled encroachment of forests might represent a problem by itself, often implying loss of cultural landscapes and habitat variety, bio and eco-diversity depletion, territorial homogenization with a loss of economic and natural resources (CONTI and FAGARAZZI, 2004).

Shrubs invasion into subalpine areas due to livestock reduction and abandonment pastures is a common process in the Northern Calcareous Alps (DIRNBÖCK and DULLINGER, 2008). Especially dwarf pine (*Pinus mugo Turra*) is able to effectively invade subalpine and alpine non-forest sites (DIRNBÖECK and DULLINGER, 2008; DULLINGER *et al*. 2003).
The abandonment of traditional grazing activities would lead to a change and reduction of valuable habitat types (OSTERMANN, 1998) and to a biodiversity loss (WATKINSON ORMEROD, 2001; TALLOWIN *et al*. 2005; MACDONALD *et al*, 2000; PORNARO *et al*, 2009).
It is demonstrated in many studies (LINDSTÖM *et al*., 1998; ZBINDEN *et al*. 2003; ZEITLER, 2003) that the management of alpine pastures is a key factor for preserving most of the present bird habitats. In the study area, the shrubs colonization of pastures affects the density and breeding success of black grouse (*Tetrao tetrix*). Black grouse habitat capacity depends on pasture management practices such as grazing, mowing, and control of regenerating tree and shrubs. Declining use and maintenance of alpine pastures leads to a reduction of black grouse populations (GLÄNZER, 1985).
In addition to the impacts on bio and eco-diversity, other negative effects are caused by uncontrolled dwarf pine expansion, such as the invasion of historical sites and the occlusion of forest roads and trails. The vegetation, if not controlled, may stop the vehicle traffic precluding the accessibility of the areas. A decline in accessibility, will riduce both the touristic value of the area with a depletion of the environmental services, and the efficiency in the management of the area.
One of the major constraints in the reclamation and correct management of the areas are the high operative costs. To maintain in good condition the pasture areas and the forest roads it is necessary to invest a lot of time and money without any apparently economic benefit.
A considerable proportion of the total cost originates from the logistics activities (transportation, storing and handling) that are particularly difficult in that condition. Productivity and cost of transportation depend on several factors, such the type of material, the type of hauling vehicle used and the characteristic of the road network (POTTIE AND GUIMIER, 1986). Logistic chain modeling is very important in improving the overall performance of the total logistic chain (SLATS *et al*., 1995).
ArcGIS Network Analyst represent a valid tool to perform analysis and solve problem related to the logistic. This tool allows to create an origin-destination (OD) cost matrix from multiple origins to multiple destinations, setting network impedance (such travel time) from each origin to each destination. Additionally, it ranks the destinations that each origin is connected to, in ascending order based on the minimum network impedance required to travel from that origin to each destination. ArcGIS Network Analyst provides a vehicle routing problem solver that can be used to determine solutions for complex management tasks and allows setting a series of descriptors (speed limit) and restriction (barriers) to modeling the transport on a road network. The routing solvers OD cost matrix is based on the Dykstra's algorithm (DYKSTRA, 1984) for finding shortest paths (ESRI, 2009).

In this paper a first approach for the reclamation of an area invaded by dwarf pine and the logistic of the operations are analyzed assuming the removal of the trees on two strips along the borders of the forest roads.
Firstly a preliminary investigation of the area and fields trials have been carried out with the objectives of:

- evaluate of the extension of the surface covered by dwarf pine;
- define of the characteristic of the forest road network;
- define the productivity of dwarf pine felling operation;

In the second part of the work the collected data have been then used to create a model for the transportation of the material under different scenarios (FIGURE 1) in order to:

- evaluate the possible logistic solution;
- evaluate the total cost of chips production.

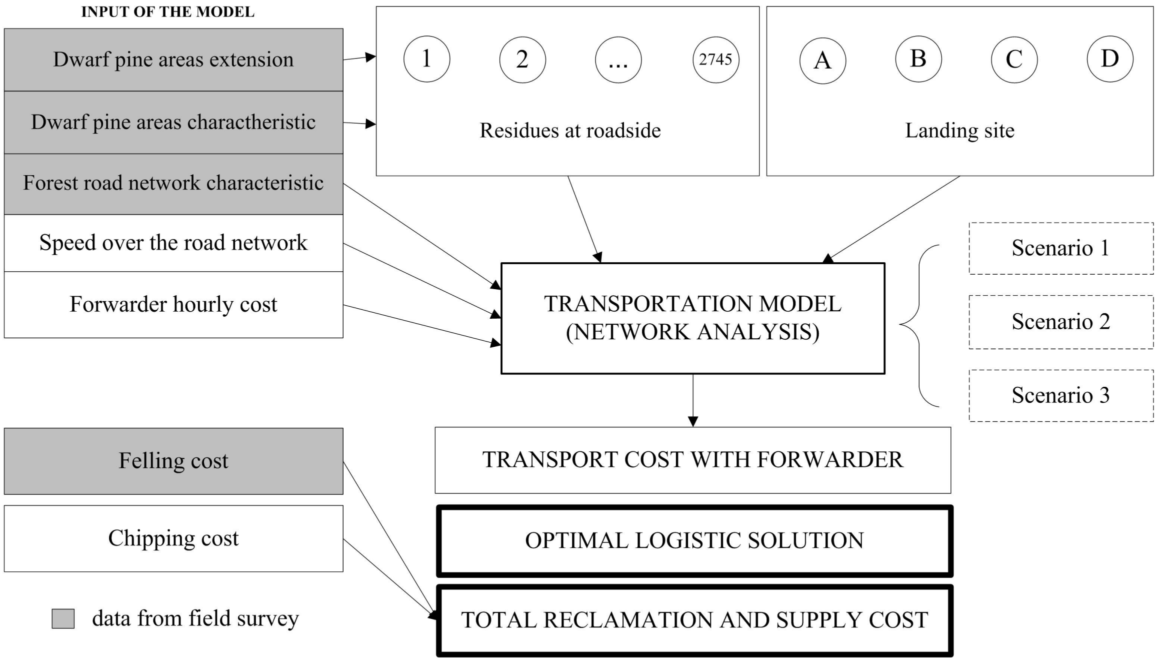

Figure 1. Layout of the study

2. Material and methods

2.1. Study area

Study area is placed in the northern part of the Altopiano dei Sette Comuni in North-eastern part of Italy (46 – 45.92° North latitude; 11.45 – 11.65° East longitude). The altitude ranges from 1 600 m to 2 341 m a.s.l..

The area is designated as Special Protection Area (SPA code IT3220036) in the Natura 2000 Network under the Habitats and Birds Directives. Tree vegetation consists in large part of a sparse forest of dwarf pine.

For centuries pastures grazed by sheep and cows in the summer covered the northern part of the area. In 19th century dwarf pine was constantly used for the production of charcoal. In the last fifty years the reduction of the demand of dwarf pine wood for charcoal production and the increasing of abandoned grassland previously used for pasture has determined the starting of the dwarf pine colonization (ZOVI, 2009).

The surface occupied by dwarf pine in the Vicenza Province according with the Regional Map of Forest Type is 2362 ha, of which 1398 ha (59%) is inside the studied area (REGIONE DEL VENETO, 2006).

For these reasons, the Altopiano dei Sette Comuni represents a meaningful case study for the effect of the expansion of dwarf pine forest over pastures, breeding area and historical sites, the last ones mainly represented by the remains of the First World War.

2.2 Site analysis

A detailed survey of the area has been done in order to analyze the situation and assume the correct "*modus operandi*".

Firstly the extension of the surface occupied by dwarf pine reported on the Regional Map of forest typology has been verified and re-digitalized after a detailed visual analysis of aerial photos followed by field validation.

To estimate the characteristic of the dwarf pine formation, five squared plots (15 m x 15 m) have been randomly selected over the study area. All the individuals of dwarf pine in each plot area have been sampled, recording for each

one the number of stems and the diameter of each stem. After the clear-cutting of each sample plot all the wood material has been weighted using a dynamometer (KERN HCB 50K20) and a wood trestle.
In each sample plot have been counted the number of trees. For each tree has been counted the number of stems and the diameter and the weight of each stem. Finally through sum of all the weight the mean growing stock has been determined. Field trials have been carried out in summer 2009.
The extension and the characteristic of the forest road network present in the area have been also surveyed.
GPS survey has been settled to collect information about dimensional characteristic of the forest road network, using a classification based on the type of machine able to transit on the road. Limiting width (transit barriers) and condition of the road have also been surveyed.
Roads have been divided in 4 class according with the risk to be invaded by dwarf pine.
Finally potential landing sites have been detected. A potential landing site should have suitable dimension (>1500 m^2) for piling and chipping the material and should be easily reachable by trucks for final transportation.

2.3 Logistic organization

The logistic chain considered for the case study is represented in FIGURE 2.
The three most important frames in the organization of the operation are the pile of material on the roadside (directly connected with the dwarf pine areas location and growing stock), the forest road network and the landings.
Distance between each felling site (FS) (in meters) has been calculated using the following formula:

$$FS = L\max \times \frac{1}{GS} \times \frac{1}{LD} \quad [1]$$

where
GS, mean growing stock of the dwarf pine areas (in t m^{-2});
Lmax, carrying capacity of the forwarder in transporting wood material (t) (limited to 4 t because of volume limitation);
LD, lateral distance reachable by the forwarder crane (m) (assumed equal to 7.5 m on each side of the road).
According to this assumption and considering the growing stock of the dwarf pine in the area, the necessary distance along the road to complete a load results 20 m. This is the length between each felling site considered in the analysis.
For the definition of the forwarder technical data has been considered a machine currently used in the area (HSM 208F 12t).

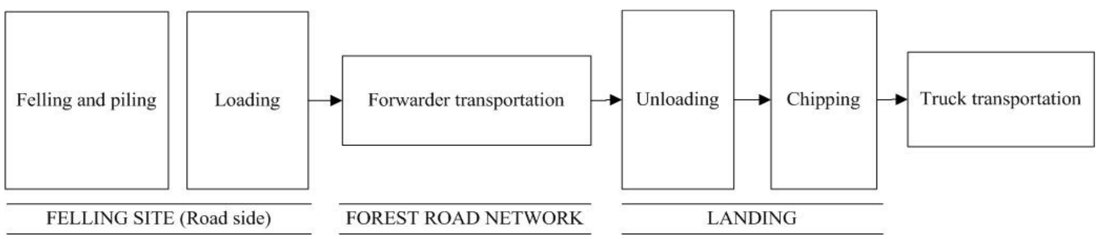

Figure 2. Assumed logistic chain

2.4 System of utilization and cost analysis

Felling and piling: the only effective way to fell dwarf pine is motor-manually using a chainsaw because the characteristic of the stem does not allow using any other system.
During the clear-cutting of the 5 sample plot manual time-study have been carried out.
In order to determine the productivity of the operation have been considered the total time (included delay) spent by a team composed of 2 chainsaw operators to completely clear-cut and pile the material in each plot.
Felling cost (TABLE 1) has been then calculated dividing hourly productivity for hourly cost of the operation.

The hourly cost of the chainsaw has been calculated applying the Miyata's methodology (MIYATA, 1980), the operator hourly cost was fixed as reported in the CCNL 2006.
The reclamation strategy plans to fell all the material within 7.5 m from each border of the forest road, being this distance easily reachable by the crane of the forwarder which stays on the road.
Forwarder transportation modeling: for the extraction of the material it is supposed to use a forwarder. The possibility to fast the loading and unloading operation, the high carrying capacity and the high speed and mobility on the forest road network highlights the convenience in using this machine.
Driving time from felling sites to landings was calculated in ArcGIS with Network Analyst tool. Different average driving speeds for the forwarder were assigned according to the characteristic (width, slope) and the condition of the roads. A range between 8 and 12 km/h have been adopted.
For each transportation cycle have been also considered a fix time for loading and unloading operation. Fix times have been estimated through interviews to the forwarder operators according with their experience in branches handling and are equal to 30 min for loading operation and 10 min for unloading operation.
Transportation cost was then calculated based on time needed for covering the route from the felling site to the landing, multiplying for the forwarder's hourly cost.
The hourly cost of the machine (TABLE 1) has been determined applying the Miyata's method (MIYATA, 1980) and using data provided by a forest enterprise using forwarder in the studied context.

Table 1. operative cost

Operation	Unit	Cost
Felling	*€ t^{-1} (w=50%)*	11.8
	€ ha^{-1}	1633
Chipping	*€ t^{-1} (w=50%)*	14.7
	€ ha^{-1}	2034
Forwarder transportation	*€ h^{-1}*	121

Chipping is supposed at landing using a mobile chipper (JENZ HEM 560 D) immediately after the felling and extraction operation to preserve the essential oils contained in the wood material. The considered chipping productivity is 64 m^3_{st} h^{-1} (NEGRIN, 2010) relative to some field trials performed in chipping of tree branches. Derived cost are reported in TABLE 1.

2.5 Scenario simulation

All previous data have been used to build a model to simulate the logistic cycle of the material from the felling to the chipping.
The input of the model are represented by the felling sites (FS - origin) the landing sites (LS - destination) and the forest road network.
A series of descriptors (speed limit) and restriction (barriers) have been settled over the forest network to simulate the characteristic of the road and the presence of point that limit the transit.
The model calculates the transport cost summing time and cost of transport and load/unloading between each origins (FS) and each destinations (LS). From the resulting matrix, the lowest cost to reach each destinations from each origin is found (output of the model).
Scenario simulation considers three different situations. Each scenario include a subset of input representative of the condition of the forest road network.
Scenario 1 represents the actual situation. Scenario 2 tests the influence of the building of a new forest road that will reduce considerably the mean transport distance. Finally Scenario 3 tests how the transport cost will change through a total upgrade of forest road network, removing all the transit barriers. Totally 36 simulation have been run.

As a consequence, the output data have been used to choose the logistic solution that minimize the total transportation cost and to construct the supply-cost curve.

3.Results

3.1 Extension and characteristic of areas invaded by dwarf pine

The extension of the areas covered by dwarf pine in the northern part of the Altopiano dei Sette Comuni has never been so wide as today, and has become a major problem in the last decades.
The surface covered by dwarf pine formation resulting from aerial photo-interpretation is 1867 ha. The expansion is continuous and uncontrolled, with an increase of dwarf pine areas being estimated in 494 ha in the last 40 years.
The results of the measures inside the study plots are presented in TABLE 2 and show a mean growing stock of 138.4 t ha^{-1}. The strategy for the reclamation of the forest road-side areas regards potentially a surface of 25 ha (16.6 km of roads considering a buffer of 7.5 m each side). The potential felled material is in this case about 3460 t (w=50%).

Table 2. Sample plot data

	D_m		H_m	T_m	Growing stock
	cm	S.D (+/-)	m	t	t ha^{-1}
Plot 1	8.1	2.49	2.81	3.04	135.1
Plot 2	7.7	2.19	2.63	3.3	146.6
Plot 3	8.7	2.59	2.84	3.74	166.2
Plot 4	7.1	2.41	2.52	2.64	117.3
Plot 5	7.6	2.58	2.67	2.85	126.6
Mean	**7.8**	**0.60**	**2.69 (+/- 0.13)**	**3.11 (+/- 0.43)**	**138.4 (+/- 18.94)**

D_m = mean diameter; H_m = mean height; T_m = total mass

In the actual situation must be considered also the limiting transit barriers on the forest road network. In this case the reclaimed surface became 20 ha and the material retrievable and transportable at the landing sites decrease to 2985 t (w=50%). Supposing a rotation time of 25 years (BROLL AND PIETROGIOVANNA, 2009) in order to guarantee a constant supply of material the reclamation will occur on 667 meter of road per year (considering a buffer of 7.5 m each side) with an amount of material equal to 138 t $year^{-1}$.

3.2 Forest road network situation and maintenance needs

The forest road density index referred to the area occupied by dwarf pine is 19 m ha^{-1}, a considerable value for an area without any particular productive vocation. Mean road width is equal to 2.8 m and the limiting transit barriers are represented manly by harpin turn and sporadic landslide point.
The considerable density of roads into the area is due to the fact that the “Altopiano dei Sette Comuni” was affected by the events of the First World War and battles followed one another for four years. In the study area the battlefront was established and it remained stable during the last three years of the war; to supply the opposed armies a diffuse road network was built on both the sides of the front. Actually it still maintains its efficiency and is used also for forest transportation and tourist access.
The part of forest road network used in dwarf pine transportation modeling resulted in 37 km. Roads have been classified considering two transit categories: roads suitable for trucks transit (24 km) and roads suitable only for forwarder transit (13 km). The forest roads suitable only for tractor transit have not been considered because not useful for the hypothesized utilization process.

Regarding the condition of the road network, 12 km of road was at the time of the survey in good condition, in 16 km the condition slightly affect the transportation efficiency and in 8 km transportation efficiency was heavily affected.
The part of the forest road network susceptible to be invaded by dwarf pine have been evaluated in about 21 km. Part of these roads (about 4 km) are already completely occupied by dwarf pine (FIGURE 3).

Figure 3. Present condition of forest roads: a) susceptible to invasion; b) partly invaded by dwarf pine; c) completely invaded by dwarf pine

3.3 Operative cost

The cost for felling and piling the material resulted equal to 1 633 € ha^{-1}. The total cost to clear-cut the entire area leaving the material at roadside is equal to 40 825 €. Considering a further processing of the wood material (i.e. essential oils distillation) the transport cost from the felling site to the landing point and the chipping cost must be added. Through addition of felling, transporting (included loading and unloading) and chipping costs, the total cost of woodchips can range in the actual situation from 52 € t^{-1} to 143 € t^{-1} with an average cost of 92 € t^{-1}. The simulation of the logistic cycle shows that in the present condition the best logistic solution would be the activation of two landing sites in point A and point B (FIGURE 4). In this case total reclamation cost, including transport at landings and chipping will be about 500 000 €.
Nevertheless cost could be considerably reduced through the activation of a third site in point D. This implies the construction of a new road (FIGURE 4) that will permit the forwarder to avoid the outflanking of a mountain that would result tactical (Scenario 2). The average total cost in Scenario 2 then decreases to 68 € t^{-1} ranging from 52 € t^{-1} to 107 € t^{-1}.
The construction cost of a new forest road is estimated in 38.5 € m^{-1} (CAVALLI AND GRIGOLATO, 2010). The intervention to update a highly debased forest road is about 15 € m^{-1}. The total cost to activate the new forest road, settling up an existing track for a distance of 1.7 km and constructing a new track 2 km long, is estimated in approximately 95 500 € and the total reclamation cost will in this case decreases to 385 000 €.
Finally the upgrading of the entire forest road network will include the improvement of the surface condition with the reduction of travel-time and the removal of limiting transit point that makes possible to add another landing site in point C (FIGURE 4). The model simulation in this case (Scenario 3) shows an increasing in the available material up to 3323 t but the transportation cost does not decrease significantly. In Scenario 3 the average cost becomes 65 € t^{-1} ranging from 52 € t^{-1} to 107 € t^{-1}.
Upgrading the entire forest road network reclaimed surface increases up to 25 ha with a total reclamation cost equal to 444 000 €.

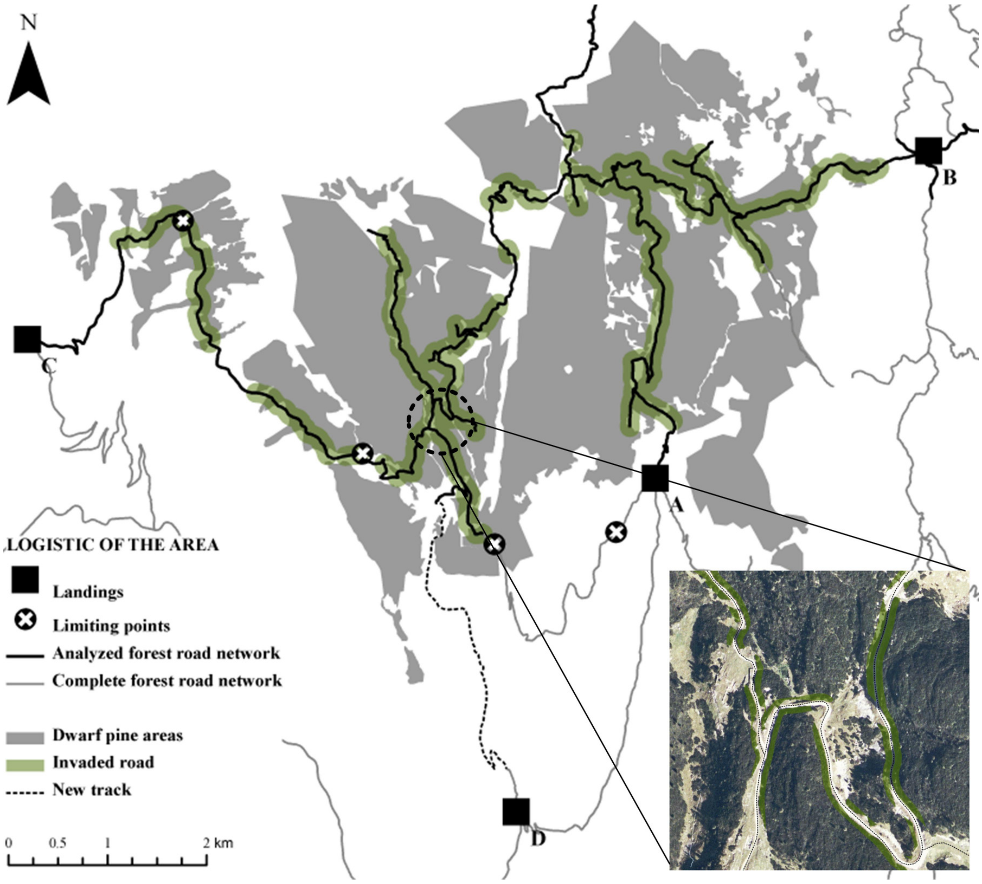

Figure 4. Analyzed area and road maintenance needs

FIGURE 5 displays the cost supply curves resulting from the hypothesized logistic solution (number of landings) for the different Scenarios. Each point of the cost-supply curve gives the average cost per ton to supply different level of chipped material.

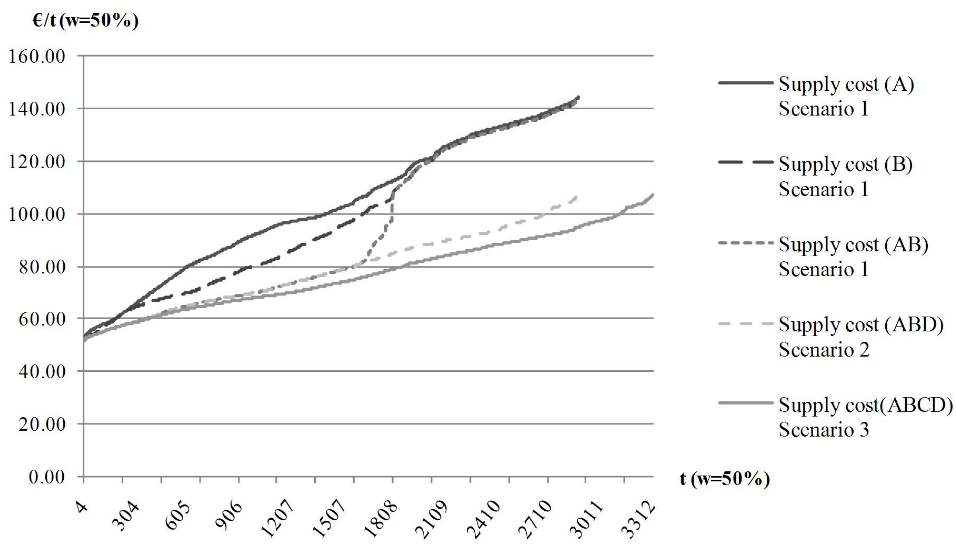

Figure 5. Supply curves for different logistic scenarios

4. Discussion and conclusion

The paper highlights that the fast expansion rate of dwarf pine is creating a serious problem in the study area. This invasion trend should be controlled, considering that most of the benefit bringing from the intervention (bio and eco-diversity benefit, social and aesthetic benefit) are not easily valuable in economic terms.
Even so nowadays the intervention for reclamation of those areas are limited, with the constraints of the high operative costs, for the costly and time-consuming process. For that reason the improved areas are very small and made mainly from game hunters or from the farmers directly involved in pasture management.
Actually financial measures such as subsides, incentives or compensation payments, that represent the main tools so far adopted by European Union, as well as by national and regional governments, in order to counteract marginalization trends and land abandonment, seem to be not sufficient.
This study is a first approach for the reclamation of areas colonized by dwarf pine considering the possibility of an hypothetic production of woodchips. The felling of the areas along the roadside seems to be the priority intervention in order to maintain in a good status the condition of the forest road network, that represent the access point for all the next reclamation interventions that could be planned in order to provide positive effect in terms of touristic exploitation and aesthetic value.
This sort of maintenance could be considered as a starting point that should be followed by removal operations also inside the dwarf pine stands or on the border between pastures and the forest.
Network Analyst resulted a valid tool to simulate the logistic of the operation, evaluate the transportation cost of the material and find the solution that minimize the total cost.
The output of the model can be used as first esteem of operative cost. The opportunity to improve the results using input data (speed, loading/unloading time) derived from field-data can also be considered in the future.
The analysis confirms that the operative cost are high, especially considering that work at roadside is the simplest situation. To remove dwarf pine trees also from the pasture's border or to maintain suitable habitats for black grouse it must be considered that recovering costs will increase proportionally with the distance from the road. A proposed solution to overcome the economic constraints would be to find an alternative use of the material. In fact the supply cost ranging from 52 € t^{-1} to 143 € t^{-1} makes the woodchips not competitive on the wood fuels market. Even the amount of 138 t y^{-1} seems to be not enough for the energy exploitation. Rather interesting is the possibility to use the material in the essential oils production, considering both the high selling price of the product and the necessity of lowest quantity of material in the production process.
This hypothesis finds support in the experience carried out in some areas in Südtirol region, where this system of production seems to work, bringing economic, environmental and landscape benefits (BROLL AND PIETROGIOVANNA, 2009).
The final step should be to activate a long-term management plan involving all the stakeholders (hunters associations, farmers, tourism associations, historical associations, wildlife ecologists) considering all the economic and environmental consequences and opportunities related to the present evolution of the landscapes.

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