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CICLO: XXXII

ECONOMIC EVALUATIONS OF NEW FOREST GOVERNANCE TOOLS:
Examples of application in the mountain context

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1 General Introduction

1.1 The Ecosystem Service concept

Ecosystems enable the production and achievement of several goods and services for the human society (MA 2003; Fisher, Turner, and Morling 2009). From food provision to basic resources for various industrial processes, they sustain life as we know it (Costanza et al. 2014). Nonetheless, goods provision represents only one of many direct and indirect benefits these complex systems provide. Known under the name of ecosystem services (MA 2003), these externalities are often overviewed in their effective value, generating suboptimal management strategies (Fisher, Turner, and Morling 2009).

Scientific research on ecosystem services (ES) represents a recent but rapidly growing field on investigation (Seppelt et al. 2011). Started in the last decade of the XX century, it now counts more thousands of works and studies (more than 2000 in the last five years[1]), with an even positive trend (Costanza et al. 2017; Bouwma et al. 2018). In consequence of such attention, the ecosystem service concept has taken root also in the national and international legislation (EC 2013; Bouwma et al. 2018; Wood et al. 2018; MIPAAFT 2019), explicitly mentioning the role and importance of such services. The adoption of an ecosystem service perspective has been used as a common ground to frame and assess over time the flow of natural resources and functions from and to the society. The current operative framework of such approach is defined by the Common International Classification of Ecosystem Services (CICES), which identifies four main ES typologies and lists all the services recognized for the various world ecosystems (Haynes-Young and Potschin 2012). According to CICES (Haynes-Young and Potschin 2012), ES are divided in:

- Provisioning services, i.e. “all nutritional, material and energetic outputs from living systems”;
- Regulation and maintenance services, i.e. “all the ways in which living organisms can mediate or moderate the ambient environment that affects human performance”;
- Cultural services, i.e. “all the non-material, and normally non-consumptive, outputs of ecosystems that affect physical and mental states of people”.

Applying this classification to forest ecosystems, which represent the main focus of the present thesis, the most relevant services results to be the timber production

[1] Data resulting from the query “Ecosystem Services” on the *Web Of Science* database on the 02/09/2019.

among the provisioning services, the carbon sequestration, water cycle regulation and natural hazards reduction for regulation and maintenance services; and finally the recreational activities among the cultural services (Häyhä et al. 2015; Plas et al. 2018). These services, together with the support given to maintain the biodiversity of the ecosystem itself, are the most assessed ES in the studies concerning forest ES (Mori, Lertzman, and Gustafsson 2017; Bianchi et al. 2018).

Nevertheless, the strong policy and academic endorsement of the ES approach has not come without debate (Silvertown 2015; Kirchhoff 2019). Even today, after more than 20 years since it acquired its current predominance, several discussion are still in place (Kosoy and Corbera 2010; Gómez-Baggethun and Ruiz-Pérez 2011; Díaz et al. 2018; Peterson et al. 2018). Most of the criticisms complain about the strict anthropocentric perspective assumed by this approach, its general unsatisfactory implementation, the limitations of the accounting methods developed hitherto and the limited emphasis on biodiversity and cultural issues (Daily et al. 2009; Kosoy and Corbera 2010; Kirchhoff 2019).

The ES concept, anyway, resulted versatile enough to address most of the environmental challenges our society is called to face (Costanza et al. 2017). Its adoption in fact eases the processes of stakeholders involvement and supports decision making processes concerning ecosystems conservation (Eastwood et al. 2016), the cultural and non-material bounds between nature and communities (Fish, Church, and Winter 2016), and eventually the implementation of mitigation and adaptation measures against climate change and natural hazards (Nyman 2015; Cohen-Shacham et al. 2016).

1.2 ES assessment and valuation

Another important feature of the ES concept, which ultimately contributed to its success, is represented by the possibility to assess and measure its characteristics in a scientifically sound way (Egoh et al. 2008; Maes et al. 2012). Most of the different ES listed in the CICES list have been investigated in their quantities, qualities and flows (Burkhard et al. 2012), through analysis at different scales, from local to global (Naidoo et al. 2008), and from different perspective, assessing the provision or the demand of the ES (Wolff, Schulp, and Verburg 2015). Nonetheless, the coexistence of different ES arising from the same environment has resulted in issues related to their different dimensions and, consequently, units of measures. Despite the possibility to bunch services afferent to the same ecosystem (Mouchet et al. 2014), the most adopted approach to pool the results of the ES assessments is represented by monetary valuations (TEEB 2010). Monetary valuations of ES consist in a group of methods used to express the value of an ES as a sum of money (Simpson 1998; Brun 2002; Pandeya et al.

2016). This assessment is achieved applying, based on the aims of the valuation, one of the several approach developed in the environmental economic discipline, which are (Masiero et al. 2019):

- Methods using benefits as proxies of the value: they estimate the value of a ES in relation to the economic benefits generated. Among these methods we have the “opportunity cost” and the “production function approach”;
- Methods using costs as proxies of the ES value: which base the valuation on the costs associated with the ES, as the costs needed to produce (or reproduce) it or to substitute it with a similar or equivalent one. Among these we have the “replacement cost”, the “substitution cost”, the “defensive expenditure” and the “avoided damages”;
- Demand-curve approaches, building the demand curve or simulating the market for a certain ES. The methods belonging to this category can be further divided in revealed preferences, or direct, methods, as the “travel cost” and “hedonic pricing”; and stated preferences, or indirect, methods, as “contingent valuation” and “choice modelling”;
- Benefit transfer methods, relying on the value of an ES of a primary study which is adjusted to the conditions of the actual study site.

During the years, different methods where successfully tested and adopted for different ES, alone or in combination. This allowed the progressive identification of one or few methods which best suit for each ES and, subsequently, to the creation of a vast literature on the topic (TEEB 2010). The current scientific research also influenced the present thesis, which adopted the most suitable economic valuation methods to assess the mountain forest ES.

1.3 Valuation of mountain forest ES

The focus area of the whole work is represented by mountain forests located within the Alpine context and the manifold ES they provide. Within the context of monetary valuations, this topic results particularly interesting for different reasons. First, there is a general gap in the scientific research concerning the economic evaluation of the manifold forest ES. Most of the studies in fact, focus on provision services as timber and CO^2 sequestration, overlooking other functions that differentiate mountain forest stand from plantations and other stand located in lowlands (Sacchelli and Bernetti 2019; Buonocore et al. 2019). Among those, the most relevant is definitely the protection against natural hazards, which in this environment are usually represented by avalanche, rockfall, shallow landslides and torrent (Bianchi et al. 2018; Moos et al. 2018). Starting from the analysis of the provisioning services (Chapters 2, 3 and 4), within the present thesis also the forest protection service against rockfall has been valuated, providing one of the first examples of standardized methodology to assess this service at stand level (see chapter 5).

Another relevant aspect to be investigated is represented by the various changes in land uses and management patterns that have influenced mountain forests in the last century (Egarter Vigl et al. 2016). Forest resources in the Alps have faced two opposite trends: first, a general period of over exploitation and deforestation, where the forest cover has been drastically reduced and the treeline lowered (Rutherford et al. 2008). Then, since the XX century, and particularly from its second half, a strong depopulation has affected mountain areas, with most of the inhabitants now concentrated in the valley bottoms (Gehrig-Fasel, Guisan, and Zimmermann 2007). This change has also influenced the demand of ES the society requested to forests, shifting from mainly provisional to a broader range of services (Häyhä et al. 2015; Keiler and Fuchs 2018). Moreover, phenomena as mass tourism, climate change and abandonment of forests and pastures have exacerbated these phenomena, urging local administrators to find complex balances between different actors and resources (Bebi et al. 2017; Kulakowski et al. 2017).

In this light, the study area we selected, mountain forests located in Piedmont region, Italy, represent an appropriate example of the current trends affecting this topic. Italian Western Alps have been deeply interested by the different trends descripted above and are currently facing severe lacks in forest management and planning, and scarce recognition of the various ES provided by forest (IPLA 2007). Currently, Piedmont is covered by xxxha of forests, which represent the xx% of its total surface; of these woods, the 91% is located in hilly and mountainous areas. Concerning their management, only xxx Forest Management Plans are currently in place in the region, covering a total area of only yyy ha. These lacks are also reflected in the limited development of the forest road network, which is lacking in the 66% of mountain forests; in the 40% of stand actively managed, below the national/European average of xxx%, and in the prevalent non-productive functions interesting the 48% of mountain forests (IPLA 2007). In this light, the importance to provide forest owners and decision-makers of innovative instruments to overcome these limitation is seminal.

1.4 Aim of the thesis and chapters presentation

In consideration of the abovementioned issues, the present PhD thesis has the objective to develop innovative models and tools for the monetary evaluation of the forest ES. The overarching goal of such studies is to provide decision-makers and forest managers of instruments to widen the available information basis and support the decision processes with informative economic data (Montagné-Huck and Brunette 2018; Thaler et al. 2019). The application of the results of the PhD is therefore expected to act on the local governance structure and functioning, improving its processes and outputs. This goal has been achieved in four subsequent steps, which consist in the chapters of the present thesis. Each of them also includes the implementation of the valuation on a case study located in various areas of Piedmont. This enabled the authors to provide consistent and replicable examples of their application at local level, critically discuss the achievements and lacks of the studies and, overall, demonstrate the benefits of an active management of the forest resources. The latter aspect has been tackled from an economic perspective, assessing costs and benefits deriving from implementing forestry operations aimed at improving the provision of one or more ES. Moreover, as rarely happened in other studies on the topic, the ES supply has been coupled with the analysis of the stakeholders' needs of ES, which represent the demand side of the valuation. Therefore, such studies allowed highlighting the added value of managed stands and the consequences of forest management on i) ES provision, ii) local economy and wood market, iii) Total Economic Value of forests and iv) their potential role in Carbon Credit Market.

Based on the framework presented in figure 1, the remainder of the thesis is structured as follows.

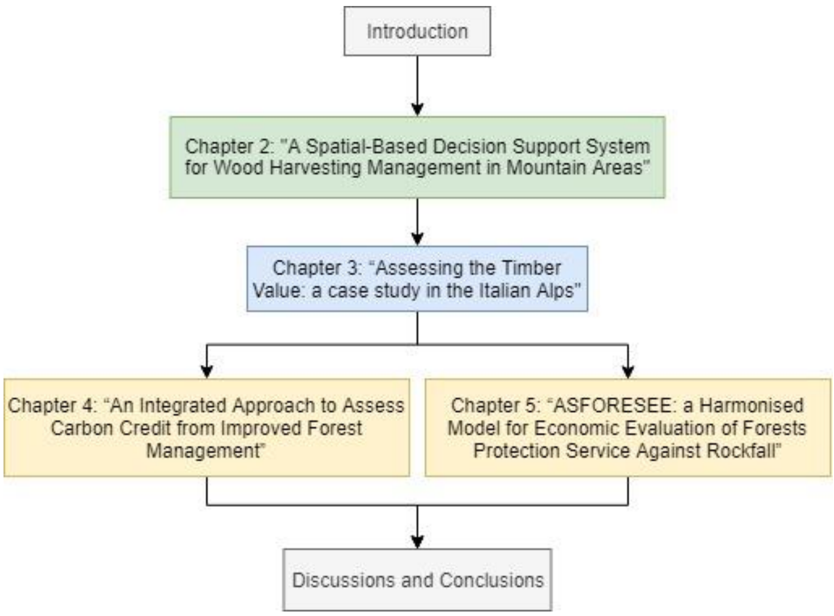

Figure 1: flow chart representing the internal organization of the thesis.

In the Chapter 2, "A Spatial-Based Decision Support System for wood harvesting management in mountain areas" is presented. This study constitutes the methodological basis where to develop the following analysis: here a Decision Support System (DSS) for forest managers has been created in order to provide the users of spatially explicit economic data on the stumpage price of different forest parcels. The DSS is able to consider alternative harvesting scenarios and recognize the influence of topographic and logistic factors on the productivity and feasibility of the forest operations.

The SEM (Spatial-base Economic Model) developed in the chapter 3 ("Assessing the Timber Value: a case study in the Italian Alps") has been applied to another case study located in the Italian Western Alps, with the aim to value its parameter with statistical analysis and test the economic results of alternative management options. Particularly, we hypothesized the harvest of a chestnut forest stand by logging companies characterised by different organizational features. Then, the input data and the results obtained served as an example to investigate the influence of the different entry parameters on the final value of the harvest. Such parameters were considered both individually, through a sensitivity analysis of the results, and adopting a Monte Carlo approach to assess the influence of different typologies of parameters in an aggregated form.

The third step of the thesis is presented in Chapter 4, entitled "An integrated approach to assess carbon credit from improved forest management". Here, once developed and tested the necessary economic tools, the model has been improved in order to integrate the assessment of the potential carbon sequestration of the stand beside its timber value. Complementing the SEM with other models, CBM to model the forest development; YAFO to maximize the revenues from the harvests and CARBOMARK to translate the stored carbon into credits, we assessed the potential profitability of a forest management oriented to carbon sequestration. This scenario was then compared with a Business As Usual option, where the forests was valued only for its timber provision, highlighting the differences in costs and revenues for their harvest and the minimum prices needed to achieve the break-even.

Finally, Chapter 5: "ASFORESEE: a harmonised model for economic evaluation of forests protection service against rockfall" consists in an alternative application of the economic model, where an additional forest ES, the protection service against rockfall, is valued. The economic model, developed within the Interreg Alpine Space "ROCKtheALPS" project, follows the path traced in the previous studies, providing a useful tool for decision makers and forest managers in the assessment of the monetary value of different ES. The ASFORESEE model stands for its ability to include the forest management expenditure into the evaluation, to develop a standardize model replicable in similar mountainous contexts and to enable the application of different economic approaches in relation to the aim of the valuation and the need for protection of the stakeholders. This study represent one of the first examples of monetary valuation of Ecosystem-based solution for Disaster Risk Reduction (Eco-DRR) in the Alps, supporting the awareness on the ES concept and its derivations, aiming for their inclusion in the local risk management strategies.

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2. A Spatial-Based Decision Support System for Wood Harvesting Management in Mountain Areas

Journal

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Keywords

Spatial modelling; mountain forest management, stumpage cost, economic valuation; DSS.

Abstract

In this paper, a spatial-based economic model is proposed with the aim of estimating the most likely harvest cost of a forest block in relation to its particular morphological and operating features. This work, which is based on the classical stumpage price assessment method, presents an economic balance of a forest cut, attained by conducting a cost analysis of each logging phase of the different standard harvesting strategies. The study area is in the North-West of Italy, in the Mount Cotolivier forest compartment, in Oulx, Piedmont. The map of the stand structure, which is included in the Oulx Forest Management Plan, was used to locate blocks (areas considered homogeneous according to the stand structure and forest typology) where silvicultural cuts could be scheduled. The feasibility of the selected logging strategies was mapped considering six conditioning factors, of both a topological and a topographic nature. Their influence was weighted by means of a score assignation and integrated in a Multi-Criteria Decision Making procedure. The scores were mathematically combined to calculate a spatial dependent cost-function (*Block Exploitation Aptitude*, *BEA*) in which the suitability of each block to be harvested was mapped through a specific strategy. The obtained *BEA* was then used to estimate the most suitable productivity rate

of the harvests of each block. The unitary costs of the strategies were estimated and then compared to find the most profitable one for each block.

This model has proved to be effective in generating objective economic results concerning harvest cuts in productive stands in mountainous areas. The proposed methodology simultaneously takes into account different factors and generates feasibility scenarios, in the space domain, for the considered harvesting strategies. The proposed model represents a prototype on which an operational *Decision Support System* could be based to assist forest managers over the short-medium term.

Highlights

- Spatial-based economic model for the estimation of harvest costs of blocks;

- The model considers the morphological and operating features of the area;

- Economic estimates are defined according to the harvesting suitability of blocks;

- The approach constitutes a Decision Support System for forest managers.

2.1 Introduction

Evaluating the exploitation costs of a forest harvest is a basic step in the stumpage price estimation, and requires several skills in different work fields, such as economy, silviculture and exploitation planning (Carbone and Ribaudo, 2005, Picchio et al., 2011). Stumpage price evaluation is generally considered to be the most appropriate methodology to evaluate mature or close-to-mature stands (López Torres et al., 2016). It has been used frequently at both international (Chang, 1983, Sessions and Sessions, 1992, Mei et al., 2010) and national level (Serpieri, 1917, Patrone, 1947, Borghese and Venzi, 1990), and it is usually adopted in forest evaluations (Carbone and Ribaudo, 2005, Carbone, 2009).

Although several works have focused on particular aspects of this estimation, such as the definition of all its components (Brun et al., 2009, Carbone, 2009) or its relationship to the purchase cost of public auctions (Brannman et al., 1987, Pettenella, 1998), only a few have attempted to relate the economic aspects to the spatial features. Few works have evaluated the Total Economic Value (Pearce, 1990, Plottu and Plottu, 2007) of a territory considering both its productive functions and ecosystem services provided, at either local (Giau, 1998, Häyhä et al., 2015) or regional level (Grêt-Regamey et al., 2008, Bernetti et al., 2013, Felardo and Lippitt, 2016). Other works, such as those by Adams et al. (2003) and Huth et al. (2005) have proposed spatial-based models that were focused on harvesting risks and impacts; on selecting the most suitable harvesting method

(Yoshioka and Sakai, 2005, Kühmaier and Stampfer, 2010), on addressing forest management and policies over large areas (Linehan and Corcoran, 1994, Puttock, 1995); or on evaluating timber availability and its harvesting costs at a regional level (Nakahata et al., 2014). However, none of these works has dealt with the estimation of the harvesting cost of logging operations at a stand level. A similar spatially explicit approach, aiming at optimizing forest management from an economic point of view, was already presented in Härtl at al. (2013). There, the stumpage price of harvests was computed in relation to the achievable timber volume, without taking in account alternative strategies of work organization and environmental aspects of stands. Similarly, the Biomasfor model (Sacchelli et al., 2013b) stands for its ability to match ecological and technical data, assessing the economic results of harvest with the stumpage price method. On the other hand, harvests are analysed at regional level, not identifying each considered stand.

The present work, which is based on the classical assessment method, presents a cost analysis for each logging phase of a forest cut, and achieves an economic evaluation of an area managed by a local forest consortium. In order to make the economic evaluations consistent for management purposes, a GIS-based Decision Support System (DSS) was set up. DSSs are becoming common tools in the environmental planning context, as they are able to integrate spatial information, economic evaluations and operational issues (Thompson and Weetman, 1995, Segura et al., 2014) to optimise managers' choices (Diaz-Balteiro and Romero, 2008). Many works concerning land use and land management (Geneletti, 2004, Borgogno-Mondino et al., 2015a, Romano et al., 2015) reported the effectiveness of these systems, and the positive consequences from their adoption have been pointed out (De Meyer et al., 2013). Their application can be very versatile depending on the aim and territorial level. For example, Sacchelli et al. (2013b) and Puttock (1995) related harvest costs to forest biomass while Pussinen et al. (2001) and Nakahata et al. (2014) analysed cost dependently from spatial scale (national to local). Moreover, to avoid subjectivity effects that can occur when non-homogeneous parameters are simultaneously evaluated (Bottero et al., 2013, Sánchez-Lozano and Bernal-Conesa, 2017), DSSs are often supported by Multi-Criteria Decision Making approaches, which allow factors pertaining to both the territory and the environment to be considered simultaneously.

In this context, an operational DSS in form of a Spatial-based Economic Model (hereafter called SEM), was developed. To create an effective operational tool able to consider the productive aspects of forest management in a mountainous environment some essential conditions had to be fulfilled. Particularly, our DSS is supposed to supply forest managers of local level information, (Costa et al., 2010); to evaluate the particular silvicultural aspects of a mountainous areas (Spinelli et al., 2013); to support harvest planning in the short-medium term and to favour positive outcomes for landowners and benefits for the local community (Carvalho-Ribeiro et al., 2010, Brukas and Sallnäs, 2012). The present model aims at describing the whole estimation process, considering territorial features and standard logging strategies. The economic results are expressed as the most likely harvest cost, in consideration of the operating features of the compartment. The adoption of SEM at a local level would represent an effective tool to support local forest managers' decisions (West et al., 2013), and would lead to several benefits concerning planning and management activities (Angehrn and Jelassi, 1994, Hung et al., 2007).

2.2 Materials and methods

2.2.1 Study area

The study area where SEM was built is located in the upper Susa valley, in the Piedmont Region, North-West Italy. The compartment, part of the town of Oulx (Fig. 1), extends over 455.62 ha, and it is included in the local Forest Management Plan (FMP), which is the current forest planning instrument. This area has a widespread road network (average density of 55 m ha^{-1}); its altitude ranges from 1200 to 2100 m a.s.l. and the main forest category is represented by larch stands (*Larix decidua* Mill.), even though Norway Spruce (*Picea abies* (L.) H. Karst.) and Scots Pine (*Pinus sylvestris* L.) stands can be found at lower, north-facing sites. Larch reforestation is at present underway on the south-facing slopes.

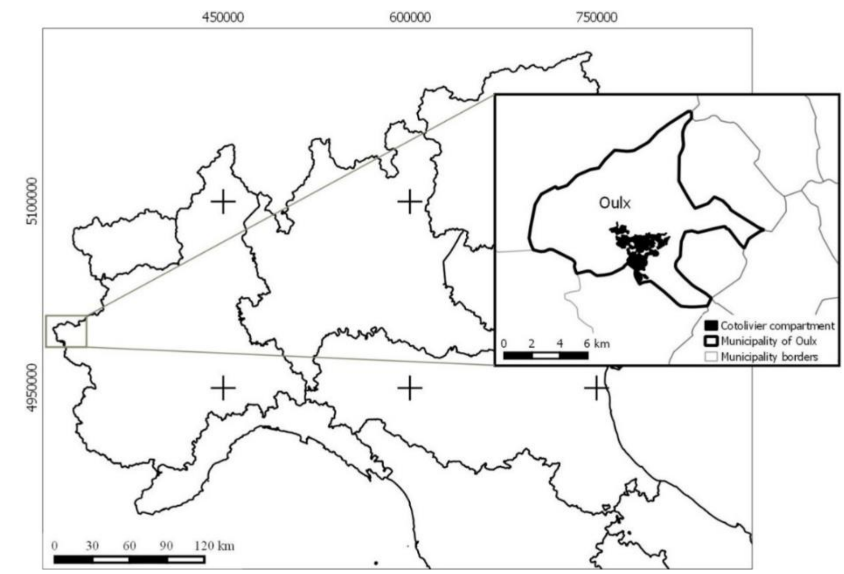

Fig. 1: Location of the study area in North-West Italy; the reference system is WGS84 UTM 32N.

This compartment was selected as a case study because of the productive destination of its forests, its favourable orographic and fertility conditions and a long-standing active management. The latter condition is due to the Consorzio Forestale Alta Valle Susa, a forest management consortium that operates in the whole Upper Susa Valley. Its presence in the area has to be considered positively, since in the Italian Alps, in spite of the steady spread of woods of the last decades (Gasparini and Tabacchi, 2011), the forestry sector supplies only 1% of the national primary sector income (Secco et al., 2017), with a wood increment exploitation of 24% (http://eurostat.ec.europa.eu). This is one of the lowest rates in Europe, even though the data should not be considered completely reliable because of illegal selling on the local firewood market (Pettenella, 2009). This general situation is leading to an increasing number of abandoned forests and under-exploited timber resources (Bätzing et al., 1996, Coppini and Hermanin, 2007), negative aspects that can be faced through an effective management and a steady timber market, two conditions ensured by the consortium.

2.2.2 Data

Since SEM was set up as an operational tool for forest managers, the considered spatial features were modelled in a GIS so they could be mapped and then related to economic and operational data.

The Map of the Stand Structure, which is included in the FMP and supplied in polygon vector format, depicts the vertical and horizontal organization of forest stands, according to their past management and stage of development (IPLA, 2003); it also divides them into blocks (Armitage, 1998). These blocks share a common stand structure, and represent the smallest management unit located by the FMP (Bagnaresi et al., 1986). Because of their dimensions and homogeneity, the blocks were assumed as the harvesting units on which silvicultural cuts are scheduled. The topographic features of the area were mapped using the Regione Piemonte Digital Terrain Model (DTM), supplied in raster format with a 5-meter grid size and a height tolerance=1.44 m (http://www.geoportale.piemonte.it). Qualitative data related to the assortments, orography, road network and timber volume of the forest blocks were obtained from the current FMP. Since the data were supplied as a text document (report), the relevant information was selected and organised in a relational database. Other inputs were obtained from: a) literature, regarding for example, technical and economic data on the organization of the logging operations, productivity and hourly costs for machines and manpower (Hippoliti and Piegai, 2000, Lubello, 2008, Blanc, 2010), and b) interviews with forest managers and workers, to define the features and limits of the considered harvesting techniques.

From an economic perspective, the stumpage price method was considered as most effective to evaluate the harvesting costs of mature forest stands, while other elements, such as ecosystem services, were not included, since they were not considered relevant for this work. Similarly, any revenues derived from timber selling were not computed either, as they are not influenced directly by the forest managers' decisions.

Several logging strategies were included in this model to identify the most suitable harvesting method. With the support of the aforementioned forest consortium, it was possible to define accurately all the fundamental technical and economic parameters in consideration of the forest and area features. The use of constant and standard values allowed the most likely estimate of the standard economic operator strategies to be built for standard market conditions (Merlo, 1993).

2.2.3 Spatial-based Economic Model

The main goal of this work was to develop an operational tool for forest management, based on both economic and spatial discriminants. Therefore, the reciprocal relationships between the discriminants were modelled by integrating information at different levels. The adopted strategy is summarized in Figure 2.

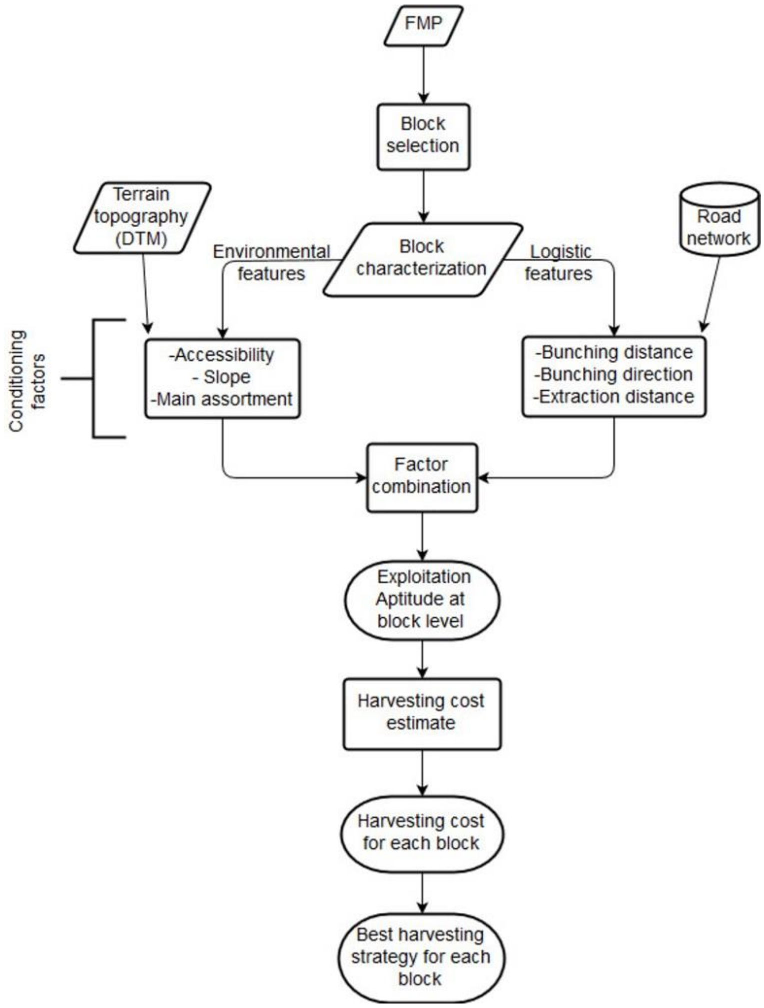

Fig.2: Flow chart of the SEM framework.

2.2.4 Forest block selection

Since SEM aims at evaluating the financial efficiency of harvesting in productive forest stands, the suitable area was defined through a block selection. First, those blocks with a non-productive destination and those smaller than 0.1 ha were discarded, since the silvicultural constraints imposed by the current Regional Forest Law (R.L. no.4 of 10/02/2009) do not allow a sufficient amount of timber to be obtained from these blocks. A second selection concerned the features of the scheduled cuts. Specific descriptors were listed for each block to qualitatively and quantitatively characterize the cuts in terms of silvicultural features and felled volume: the areas that showed a low cutting intensity were discarded (Lubello et al., 2008). These thresholds were defined according to the statements of the forest managers of the area, considering the achievable m^3 ha^{-1} of timber with regard to cut typology. Blocks with a smaller harvest volume than 50 m^3 were also excluded. This value was considered as the lowest possible to guarantee the economic sustainability of logging operations in the study area for the local companies (Lubello et al., 2008).

Attempting to increase the number of suitable blocks, it was also hypothesized that new temporary extraction tracks could be created. Any possible road network upgrade would depend on the dimensions and shape of the blocks, on their accessibility, on the present road network and on the slope of the terrain (Olsson, 2007, Chung et al., 2008). The new tracks were manually traced in a GIS editing session. Owing to the features of these new roads, which are generally located in difficult areas, as far as their morphology and accessibility are concerned, only tracked tractors can be used. However, because of their characteristics, these machines are not allowed to use truck roads.

2.2.5Harvesting strategies and limitations

The standard harvesting operations in mountainous areas are organized in three stages: a) felling and processing (FP) b) bunching (B) and c) extraction (E) (Akay, 2005, Nakahata et al., 2014). FP is performed by cutting the tree, delimbing its branches, topping the trunk and bucking it to the merchantable assortment; B consists of collecting the trunks and transporting them to the landing site on an extraction track; during E, logs are hauled to a truck road. While FP can be achieved in a single step, other stages can be performed with different techniques, depending on the working organization and territorial features.

Ten standard harvesting strategies were selected for this study and coupled with the required machinery, namely, tractors, tracked tractors or skidders (Spinelli et al., 2006, Montorselli et al., 2010). The different machineries are listed in table 1; the FP operations were performed in the same way for all of the different strategies.

Tab. 1: All the standard harvesting strategies are listed, and the B and E methods considered for each strategy are shown. The second machine listed in strategies G, H, I and L is only needed for those harvest sites where temporary extraction tracks are not connected to a truck road.

Strategy	**Bunching**	**Extraction**
A	Manual logging	Forwarding (tractor)
B	Manual logging	Skidding (tractor)
C	Direct winching (tractor)	Forwarding (tractor)
D	Direct winching (tractor)	Skidding (tractor)
E	Manual logging	Forwarding (skidder)
F	Direct winching (skidder)	Skidding (skidder)
G	Manual logging	Forwarding (tracked tractor + tractor)
H	Direct winching (tracked tractor)	Forwarding (tracked tractor + skidder)
I	Manual logging	Skidding (tracked tractor + tractor)
L	Direct winching (tracked tractor)	Skidding (tracked tractor + skidder)

SEM does not consider other strategies, such as skyline yarding or cable logging. In fact, only the standard logging methods for Cotolivier forest stands were taken into account.

The operational feasibility of the above-mentioned strategies was defined considering six conditioning topographic and topological factors. These factors were considered able to describe the silvicultural and topologic aspects that influence the logging operations. These factors were taken from literature (Kühmaier and Stampfer, 2010, Synek and Klimánek, 2015) and integrated with the forest managers' statements. Each factor was represented by a spatial dependent function, formalized in the shape of a raster map (10 m grid size), by processing, through GIS spatial analysis tools, the available maps (DTM and Map of the Stand Structure) and database: in this way, a factor was assigned to each pixel of these maps. Table 2 reports the characteristics of each factor: their values were obtained from literature (Hippoliti and Piegai, 2000, Yoshioka and Sakai, 2005, Blanc, 2010) and then adjusted specifically on the study area, through on-field surveys and interviews with harvesting specialists (Mendoza and Prabhu, 2000, Azizi et al., 2015). The FP stage is not mentioned among the factors related to logging operations since it was hypothesised not to introduce any higher constraints than those required to perform B and E.

Tab. 2: Description of the factors that condition the harvesting operations.

Raster Map Name	Information type	Description	Parent map	Factor values
$A_g(x,y)$	*topological*	Block accessibility related to rocks in relation to tractors	FMP	0.33 = high 0.66 = medium 1 = low
$A_s(x,y)$	*qualitative*	Main assortment of dimensional parameters (diameter and length), derived from the Stand Structure Map	FMP	High: d >40 cm, L >6 m Medium: d]30,40] cm; L]4,6] m Low: d<30 cm; L <4 m[2]
$S(x,y)$	*topographic*	Local slope values calculated from DTM	DTM	<20% = class 1]20,40%] = class 2]40,60%]= class 3]60,80%]= class 4]80,100%]= class 5 >100% = class 6

[2] (Continues)

$B_d(x,y)$	*topological*	Maximum bunching distance from the felling site to the nearest landing site on a track or road	DTM	0-150 m for manual logging 0-100 m for direct winching
$B_r(x,y)$	*topological*	Bunching direction, upward or downward to the nearest track or road	DTM	Downward for manual logging *Uw* or *Dw* for direct winching
$E_d(x,y)$	*topological*	Maximum extraction distance from the landing site to the nearest truck road	DTM	0-500 m for skidding 0-5000 m for forwarding

The factor values were linearly rescaled to a common range [0 – 9] (Borgogno-Mondino et al., 2015b), assuming 0 as the lowest score, in terms of strength (feasibility of the considered logging strategy), and 9 as the highest one, according to a scoring approach that is commonly used in the Multi-Criteria Decision Making context (Kangas and Kangas, 2005, Mendoza and Prabhu, 2000). These methods have extensively been employed to support forest management (Kangas and Kangas, 2005, Diaz-Balteiro and Romero, 2008), and are mainly focused on computing and locating woods that have to be harvested (Yoshioka and Sakai, 2005, Sacchelli et al., 2013b) or on optimising the decision planning in consideration of multiple purposes (Pukkala and Miina, 1997, Angelis and Stamatellos, 2004). In the present work, this approach allowed to obtain a single value summarizing the suitability of the forest blocks to be harvested (Pauwels et al., 2007). Scores were assigned to the factors according to the literature on the forestry sector in Italy (Hippoliti and Piegai, 2000, Lubello, 2008, Montorselli et al., 2010).

2.2.6 Mapping the harvesting aptitude

Raster maps of rescaled values were then combined within a specific space-dependent function to obtain an overall evaluation of the suitability of forest stands to be harvested. This aptitude was mapped for each block through the mixed additive-multiplicative model (Malczewski, 2006) (see eq. [1]).

Adopting GIS tools, all the pixels in which at least one factor value had been set to zero were masked out, as harvesting was not possible in those areas (Azizi et al., 2015). An aptitude map was then obtained by combining the masked raster layers, using a mathematical formula in which factors with the same weight were assumed (Borgogno-Mondino et al., 2015b). Factors related to the intrinsic features of the stand *(Ag(x,y), As(x,y), S(x,y))* and those depending on the harvest strategy *(Bd(x,y), Br(x,y), Ed(x,y))* were separately considered. A cumulative relationship was hypothesized among factors of the same type (intrinsic or harvest dependent), while a multiplicative effect was considered appropriate to describe the reciprocal influence of the two parts of the formula (Malczewski, 2006).

Since SEM operates in the space domain, the combination of the above mentioned raster layers according to [1] generates a new raster map in which the aptitude of each cell to be harvested is measured through a specific strategy, hereafter called “Block Exploitation Aptitude” *(BEA(x,y))*.

$$\boldsymbol{BEA}(x,y) = [A_g(x,y) + A_s(x,y)) + S(x,y)] \cdot [B_d(x,y) + B_r(x,y) + E_d(x,y)] \quad [1]$$

Where *BEA(x,y)* is the local Block Exploitation Aptitude (overall score);

$A_g(x,y)$ is the block accessibility;

$A_s(x,y)$ is the main assortment achievable;

$S(x,y)$ is the local slope value;

$B_d(x,y)$ is the maximum bunching distance from the felling site to the nearest track or road;

$B_r(x,y)$ is the bunching direction, upward or downward to the nearest track or road;

$E_d(x,y)$ is the maximum extraction distance from the landing site to the nearest truck road

The BEA values of the pixels were linearly rescaled to between 0 and 1 (Zadeh, 1965, Ananda and Herath, 2009). In order to supply the BEA at block level, the values of pixels were averaged and included in a map in which the aptitude of the blocks to be harvested was recorded. It is worth noting that a different BEA was calculated for each harvesting strategy, so several exploitation maps were generated.

2.2.7 Cost calculation and comparison of the strategies

SEM considers the entire forest exploitation process, estimating the overall harvesting cost a logging company has to cover from the acquisition of the harvesting rights up to the sale of the extracted timber (Brun et al., 2009, Proto and Zimbalatti, 2016). The overall costs were estimated considering the standard factors involved in harvesting: it can therefore be assumed that the results are only correct if the factors remain constant (Carbone and Ribaudo, 2005). The estimation of the hourly yields of logging operations is one of the main issues that have to be faced when computing the stumpage cost. The evaluation of the productivity rates of the hypothesized harvests was based on the above-mentioned BEA. This index was related to the hourly yield of the logging operations through a linear function, and, in this way, a simplified but objective value of work productivity was achieved.

The standard organization of strategies was defined by quantifying the necessary manpower and machines: a) 2 workers equipped with chainsaws are required for the FP phase; b) 2 workers are required for the B phase, considering that they can operate: i) without any engine-machines (manual logging); ii) with a winch and tractor; iii) with a winch and tracked tractor and iv) with a winch and skidder (Spinelli et al., 2006); c) the E phase can be operated by a variable number of workers, depending on the situation: i) one worker for forwarding with a grapple loader and trailer; ii) two workers for skidding, adopting the following options: a winch and tractor, a winch and skidder or a winch and tracked tractor.

The hourly costs of the machines and manpower (table 3) were obtained from literature (Spinelli et al., 2006, Piegai et al., 2008, Sacchelli et al., 2013a) and from regional standard cost tables (Piemonte, 2014). The hourly wage of the workers includes all the taxes and extra costs that are typical of craftsman contracts. The general and administrative costs were estimated to be 10% of the partial harvest costs (Brun et al., 2009). They include on-field surveys, auctions, work safety activities, supervision, financial costs and bank guarantees.

Tab. 3: Unitary costs of the machines and workers involved in the harvesting operations.

Worker/machine	**Hourly cost (€ h^{-1})**
Qualified worker	16.53
Non-qualified worker	15.71
Small size chainsaw	2.00
Medium size chainsaw	3.38
Tractor with winch and driver	47.31
Tracked tractor with winch and driver	60.17
Tractor with grapple loader and driver	59.80
Skidder with grapple loader	42.80
Trailer (140 q)	19.64
Winch	3.94

The economic and productivity factors were then combined to generate the overall harvesting cost at a block level for any strategy. In other words, the number of workers and machine working hours necessary to accomplish the intervention was calculated for each strategy. These values were multiplied by the corresponding hourly costs, and summed to obtain the overall exploitation cost. In order to define the unitary cost of the harvest (expressed in € m^{-3}), this overall amount was related to the harvested timber volume (m^3). This allowed different management strategies to be directly compared: thus, the spatial distribution of the strategies and related costs defines exploitation “scenarios” of the area.

2.3 Results and discussion

2.3.1 Cost-strategy generation

Adopting the previously mentioned selection criteria, we found 275 suitable blocks on Mount Cotolivier. Hence, SEM was applied to 366.63 ha, representing 80.46% of the study area (455.62 ha). According to the FMP data, a prescribed yield of 14834 m^3 could be obtained from these blocks. The reduction of the harvesting area is mainly due to limitations related to the Map of the Stand Structure: in fact, the reduced size of its blocks occasionally prevented us from scheduling cuts that were large enough to ensure their economic sustainability.

Among all the 275 blocks, SEM was able to locate 86 blocks with 226 feasible harvests typologies (31% of the total amount), covering 157.61ha. The total achievable yield from the suitable blocks located by SEM is equal to 6490 m^3. This represents 44% of the overall FMP prescribed yield, located on just 34% of the study area. This estimated volume would represent a strong improvement if compared to the current exploitation rate of the area of the12% (personal communication of the forest consortium). This value, together with the spatially explicit results of the model, can also be considered a useful outcome of the model, since it could support an optimized allocation of the harvests, increasing potentially the timber production. In fact, supplying an overall view of the harvestable area from an economic perspective could help scheduling the simultaneous exploitation of contiguous areas with similar features, with the same strategies, or planning patchwork exploitations in order to reduce their visual impact.

Maps showing the suitable areas and correspondent unitary costs (€ m^{-3}) of the 10 strategies are reported in Figure 3. The results prove that SEM is able to provide indications about the most suitable strategies for different areas of the compartment according to their features. On the basis of their simple organization, the firsts 4 considered strategies (A, B, C and D) were found to be the most effective and versatile ones; they can be applied to 45, 24, 75 and 44 different forest blocks, respectively. This outcome could be ascribed to the typology of the extraction operation that was adopted, since the use of a tractor has been scheduled for all of them. Strategies E, F, G, H, I and L scored fewer than 40 exploitations, and these generally suffered from high operating complexity and a low hourly yield. E and F were found to only be feasible on 10 and 17 blocks, respectively, with the latter ensuring lower harvesting costs, due to its higher mechanization level. These strategies resulted to be suitable for blocks close to the main road network and with a slight slope, due to the characteristics of the used machines. On the other hand, the remaining strategies (G, H, I and L) are only feasible on a few forest stands far from truck roads and with steep slopes. For these reasons, from an overall point of view, the possibility of adopting these strategies may be discarded.

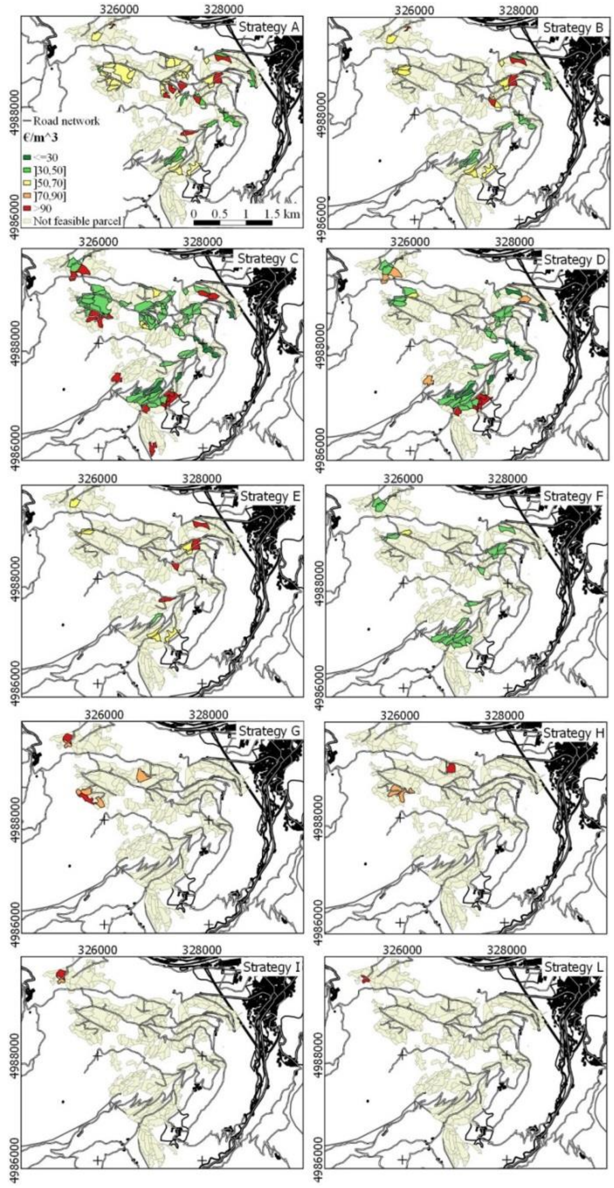

Fig.3: Maps of the cost-scenarios for the considered strategies. The reference system is: WGS84 UTM 32N.

2.3.2 Performance and limitations of the model

The two scenarios that have been generated by SEM at a block level are: a) the location of the most convenient strategy (figure 4); b) the recognition of the lowest unitary harvesting cost, which has been achieved by adopting the most convenient strategy (figure 5). Apart from the main result, a map of the highest *BEA* score for each block has also been generated and archived.

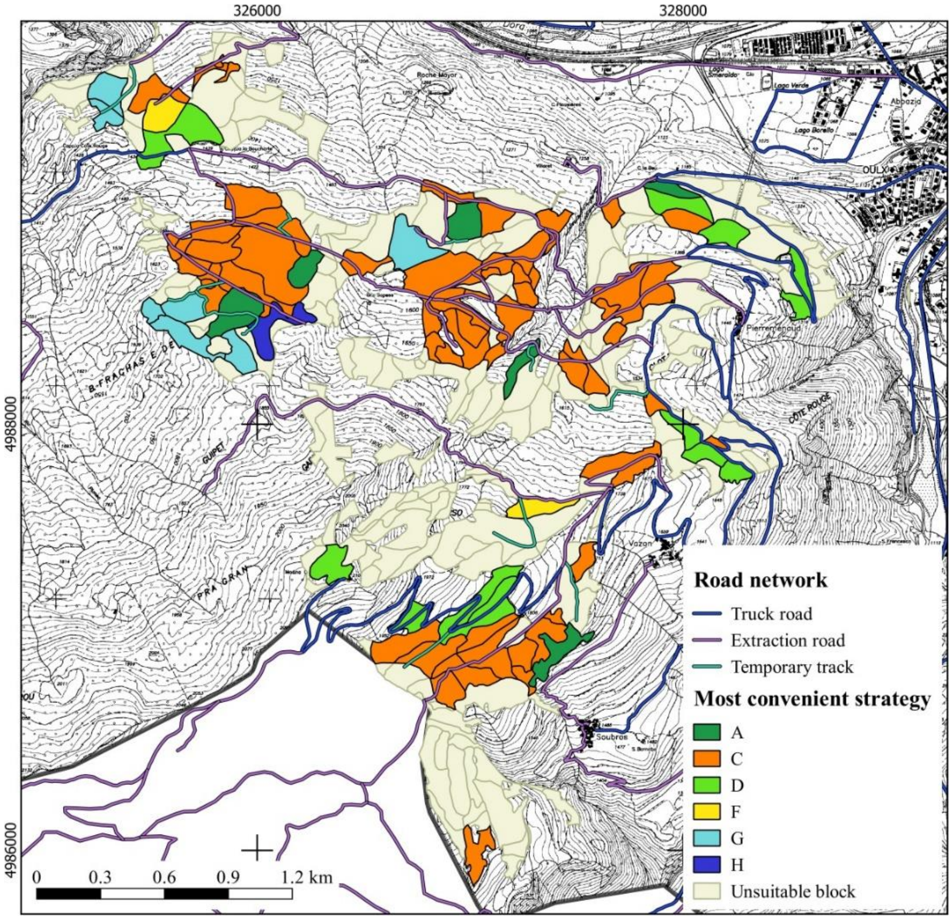

Figure 4: Map of the most convenient strategy for each block; the reference system is: WGS84 UTM 32N.

The strategy that ensures the lowest unitary cost was found by comparing the various generated cost-scenarios. Method C, which employs machines with low hourly costs and high versatility to operate in different conditions, has been found to be clearly the most convenient for 59 out of the 86 blocks. Moreover, the location of several contiguous blocks with the same strategy, as highlighted by SEM, could represent a further benefit. Planning their exploitation together or in sequence would probably ensure an additional decrease in the harvesting costs, because of the possibility of replicating the same organization. B, E, I and L always determine higher unitary costs, and therefore do not result to be the most convenient in any of the scheduled cuts. On the other hand, strategies as G and H resulted the most convenient ones for most of the blocks (8) where they can be potentially adopted (10). This situation may be related to the specific features of these areas, which are characterized by steep slopes, difficult operating conditions but proximity to temporary tracks. These strategies are the only ones that are able to satisfy the high technical requirements necessary to harvest in those areas.

Table 4 shows some statistic data pertaining to the most convenient strategies identified by SEM in relation to forest blocks, harvestable areas and achievable timber volumes.

Tab. 4: Statistics concerning the best harvest strategies for the 86 considered blocks.

Strategy	**Frequency**		**Total area**		**Prescribed yield**	
	[n]	*%*	**[ha]**	*%*	**[m^3]**	*%*
A	6	*7.0*	13.0	*7.8*	565	*8.7*
C	59	*68.6*	103.0	*61.9*	4009	*61.8*
D	11	*12.8*	26.7	*16.0*	695	*10.7*
F	2	*2.3*	4.9	*2.9*	194	*3.0*
G	7	*8.1*	16.0	*9.6*	822	*12.7*
H	1	*1.2*	3.0	*1.8*	205	*3.2*
Total	**86**	***100***	**166.4**	***100***	**6490**	***100***

Strategy C achieves the best results, for 59 blocks, for an area of 103 ha and more than 4000 m^3 of extracted timber. The second most frequent strategy refers to the blocks where strategy D is the most convenient, but the corresponding amount of timber volume is generally lower (less than 700 m^3 from 11 cuts). The A and G strategies are the most convenient for 13 blocks, where they ensure the exploitation of more than 1300 m^3 of timber. The least frequent strategies are F and H, due to the unsuitability of employing a skidder in this compartment, and to the specific conditions of the road network. Of the 10 considered strategies, 4 of them are not convenient in any of the blocks. Particularly, for B, E and I the same bunching operation is prescribed, namely the manual logging, so we can suppose this method is, generally, not suitable for the area. This is probably due to its favourable orographic conditions. In fact, low slope values and high assortments dimensions characterized most of the Cotolivier stands, influencing negatively the adoption of this methodology. On the other hand, three of the most frequent strategies (A, C and G) perform timber extraction by tractor and trailer. This element, which is common to all of these successful strategies, can be probably related to the widespread road network of the compartment, where several truck and extraction roads are present.

The definition of the most convenient strategies of each block allowed the related unitary harvesting costs to be highlighted. The monetary results were divided into 5 cost classes: <=30;]30,50];]50,70];]70,90] and >90 € m^{-3}. Figure 5 shows how these classes are spread over the study area.

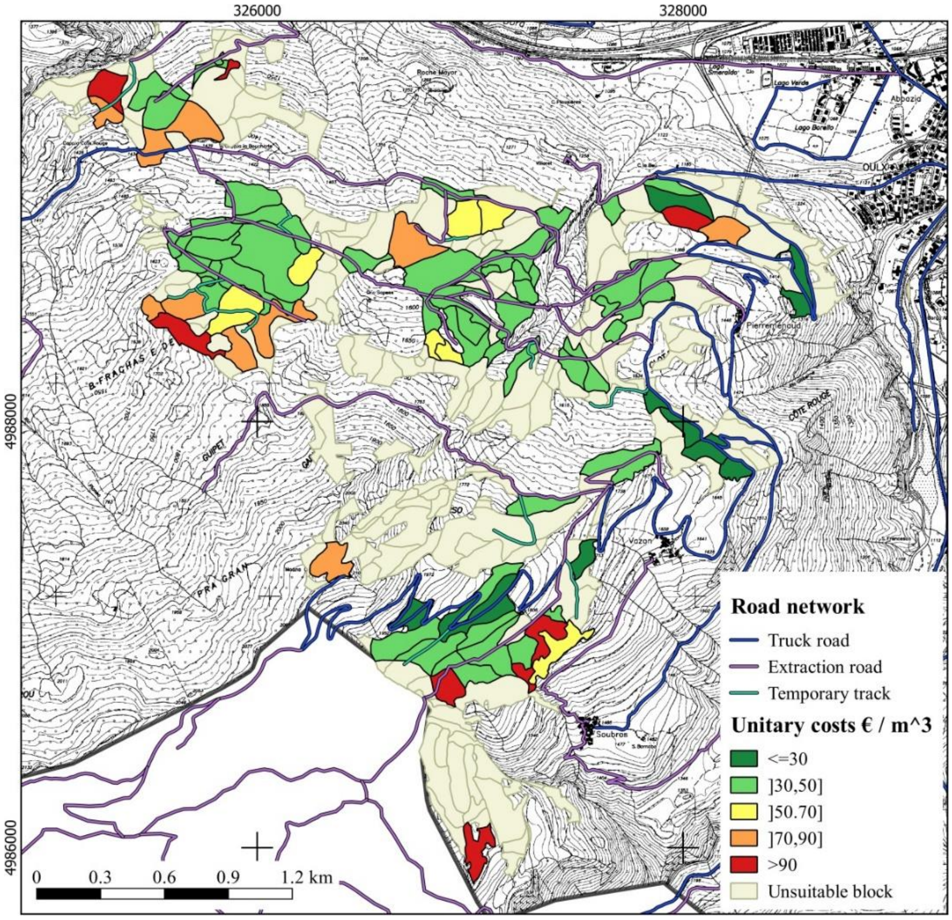

Figure 5: Map of the unitary harvesting cost of each block when the most convenient strategy is applied; the reference system is: WGS84 UTM 32N.

The cost class [30,50] € m^{-3} is the most common, with 53 exploitable blocks, which correspond to 61% of the suitable area. Overall, more than 100 hectares can be harvested in the two lowest cost classes, mainly by adopting strategies A, C and D. On the other hand, less than 20 hectares (8 blocks) present higher unitary costs than 90€ m^{-3}, where strategies G and H are the most convenient.

Some statistics concerning *BEA* and the corresponding unitary costs are reported in table 5.

Tab. 5: Frequency, exploitation aptitude and unitary costs for the most convenient strategies.

Strategy	***BEA***					**Unitary cost**			
	[n]	***Mean***	***MIN***	***MAX***	***CV%***	***Mean***	***MIN***	***MAX***	***CV%***
A	6	0.57	0.43	0.82	*24.7*	54.54	36.58	66.93	*19.6*
C	59	0.52	0.30	0.82	*24.0*	46.80	23.55	129.10	*44.8*
D	11	0.61	0.49	0.73	*13.8*	42.70	24.64	86.06	*63.4*
F	2	0.61	0.59	0.64	*6.0*	42.14	41.80	42.48	*1.1*
G	7	0.50	0.39	0.75	*25.7*	96.29	72.64	164.28	*31.8*
H	1	0.43	0.43	0.43	-	80.64	80.64	80.64	-
Total	**86**	**0.54**	**0.30**	**0.82**	***23.7***	**51.13**	**23.55**	**164.28**	***50.3***

BEA varies from 0.30 to 0.82, with a coefficient of variation of 23.7%. If the *BEA* range is split into quartiles (Q4: very low *BEA*, from 0.00 to 0.24; Q3: low *BEA*, from 0.25 to 0.49; Q2: high *BEA*, from 0.50 to 0.74; Q1: very high *BEA*, from 0.75 to 0.99), none of the stands belongs to Q4. Strategy C, which is the most frequent one, shows a *BEA* value ranging from the minimum (0.30) to the maximum one (0.82) among the possible harvests. Other strategies, such as D and F, present high/very high *BEA* values and low CV%; differently, G and H strategies are characterized by the lowest mean *BEA* values. In general, a mean value of 0.54 indicates that the overall destination of the compartment is timber production, with the most of the stands in Q2.

These *BEA* values influence heavily the unitary costs. In fact, the lowest costs are related to the strategies with the highest *BEA*, i.e. D and F. Nevertheless, some strategies show very high maximum unitary costs, probably due to the complex organization of the logging operations (G and H) or to the high variability of their *BEA* values (strategy C). The mean unitary costs for each strategy vary from 42 to more than 95 € m^{-3}, with a CV% in the range 1-63%, because of the heterogeneous working conditions. The mean cost of the whole compartment (51.13 € m^{-3}) was obtained weighting the costs of each single strategy against the correspondent achievable timber volume, in order to obtain a reliable overall evaluation of the area.

As expected, *BEA* has been found to be inversely related to the unitary costs through a linear function (Fig. 6), and may be considered as a good indicator of block harvesting aptitude, as well as for estimating the harvest costs.

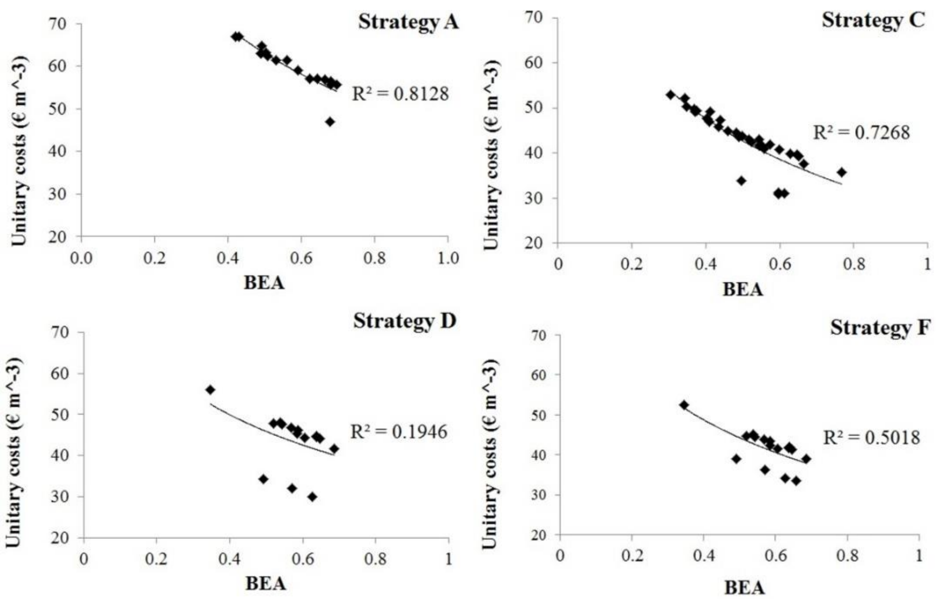

Fig. 6: Relationship between the unitary costs and BEA for the 4 most frequent strategies (A, C, D and F).

The graphs in figure 6 show that a close relationship emerges between *BEA* and the unitary costs for strategies with a significant number of harvests (>10). The coefficient of determination (r^2) shows high values, thus further demonstrating the variation of the unitary costs by *BEA*, even though some outliers may negatively influence it[3]. Even the strategies not included in figure 6 are linearly related to *BEA*, but the limited number of blocks where they can be adopted was not considered enough to ensure statistically valid results.

In the local context where it has been applied, SEM has proved to be a particular kind of DSS, focusing on evaluating harvest costs at a block level, and supplying monetary results closely related to the environmental and orographic features of the area. Moreover, the model generated objective exploitation costs of a mature forest in a mountainous area, and mapped the lowest logging costs at block level. The obtained outcomes represent fundamental information pertaining to the estimation of the stumpage price, since they include technical and economic aspects related to forest harvesting that can be used to address the management operations of a compartment. Finally, SEM, through an objective analysis based on the particular features of the study area and its standard strategies, was able to estimate hourly yield values.

Although the results achieved by SEM have proved to be consistent and suitable to support managers' decisions, the model still suffers from some limitations that suggest the need for future improvements. The most important limitation is related to the notable decrease in harvestable area in consideration of the number of selected blocks (86 out of 275). It is believed that this decrease is due to the several limitations imposed by the conditioning factors that SEM considers to guarantee the feasibility of the strategies. In fact, only those blocks considered suitable for harvesting over the current FMP validity period (10 years) by means of standard logging techniques were mapped. The result would be different if more strategies, such as skyline yarding or cable logging, or a different number of workers were considered. To date, the considered strategies represent the standard situation in the area; we believe that introducing unusual or different harvest strategies might not be representative of the normal operating conditions. Other limitations pertaining to SEM can be synthesized as follows:

[3] These outliers cannot be considered a drawback of the model, but are instead due to the absence of the WE phase in those blocks that are located next to a truck road.

- an operating FMP of the study area is required to map stand structure; in fact, without it, the location of blocks has to be edited manually;
- contiguous and similar blocks have to be separately considered; the possibility of aggregating them in larger harvests would probably a) increase the overall harvested area, b) reduce exploitation costs and c) optimize compartment management;
- factors involved in the *BEA* computation were not weighted and values assigned to the conditioning factors suffer from a certain degree of subjectivity. In particular factors selection, value and interaction remain a sensitive point that SEM users have to face. We believe that this uncertainty could be reduced if any information from actual case study in the area were available. According to these, one could consequently modify values in SEM.
- productivity rates were assumed as linear and directly proportional to BEA values; this heavy simplification probably introduces some strong approximations into the evaluation of the correct hourly yields. In fact, some works report that trend cannot be considered perfectly linear (Sacchelli et al., 2013b). It is our intention to focus on this topic in future studies in order to better define the nature of the connection between these two elements;
- considered period is probably too short; in fact, all the interventions have been hypothesized as being feasible in the short term according to the current stand conditions. This implies that probably more profitable harvests in the medium or long term have be considered, making SEM more robust and general. From this point of view, SEM confirmed to be an effective operational tool for mature forest stands rather than for long-term management purposes.

Nevertheless, since the aim of this work was to maintain a light framework and generate comprehensible results for users, these issues were deliberately simplified. In spite of these limitations, the monetary values estimated by SEM have proved to be consistent with those estimated autonomously by the forest consortium technicians in this area. The peculiar characteristics of SEM allowed us to reach a level of information useful to forest managers, as needed for an operational tool. Anyway, since the results depend on block classification based on *BEA* values, if any improvement can be achieved, it will necessarily rely on the *BEA* formula.

From the users’ perspective, SEM allows forest managers to compare different options in order to identify the most convenient one, and to obtain valuable information that can be used to address exploitation strategies at a block level.

Moreover, since the design of SEM is based on a multi-criteria approach, further implementations are still possible. In fact, the model can be easily integrated with *ad hoc* machines or strategies, with their related costs and productivity rates, in relation to the standard methodologies of the considered area. Anyway, since SEM operates locally, its application to different areas would require a revision of all the involved technical and monetary parameters. The *a-priori* knowledge of the area is thus necessary to ensure a good performance of SEM. Consequently, a strong and continuous dialogue between forest managers and the other stakeholders should be maintained and fostered.

2.4 Conclusions

DSSs can be fundamental instruments to deal with management optimisation at different area levels. In this direction, we believe that the outcomes provided by SEM could be used to read forest stands in an innovative way, supplying a tool able to link objectively harvest costs and spatial features of the area. The spatially explicit design of the model allows mapping monetary results making easy comparison of different scenarios and offering an effective operational tool for optimising harvesting operations in the short period. Nonetheless, even though SEM can assist forest managers in making better choices, it cannot replace on-field surveys that are required before scheduled harvests. For this reason, as previously already stated, we believe that a close connection between managers, stakeholders and territory is fundamental to achieve reliable outcomes from SEM and address properly management decisions.

The adoption and testing of SEM in new areas, together with its improvement, will undoubtedly strengthen its theoretical basis and the reliability of the results, thus making its adoption into normal forest management activities possible. Nevertheless, the application of SEM to different contexts will only be possible after the calibration of the required data in relation to the local standard strategies and FMP. We believe that, in the future, similar approaches to SEM could represent operative tools that could be used to support forest managers in the short and medium-term planning of productive stand activities, thus valorising the role of spatial information on management activity decisions.

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3. Assessing the Timber Value: a Case Study in the Italian Alps

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Abstract

In the Piedmont region, in North-West Italy, the abundance of unmanaged woods has led to negative environmental and economic consequences, generating a decrease in the ecosystem services supplied and in the provision of low-value timber products. In this context, increased logging activities could create new development opportunities for the rural areas in which most of the abandoned stands are situated. This work analyses a forest harvest by creating a model to evaluate its Timber Value. The economic results were analysed to investigate the structural and logistic factors influencing the profitability of a harvest. The results obtained revealed that a small profit margin is achievable for small local logging companies, even if strongly influenced by the hourly costs of labourers. To quantify the influence of each factor of the model on the timber value, a sensitivity analysis was performed. Then, to test the robustness of the results a Monte Carlo simulation was carried out simultaneously varying the factors involved. Finally, a scenario analysis was performed, in which the standard conditions referring to the most common private forest company typologies were examined. Overall, these methods were found to be suitable for our aims and capable of supplying important results to analyse a forest harvest from an economic perspective.

Keywords

Timber value; sensitivity analysis; forest harvest; Monte Carlo simulation; Italian Alps

Highlights

- A model to compute the Timber Value of a harvest in chestnut coppice was built

- The model was statistically analysed to measure the influence of factors on its results
- Sensitivity Analysis, Monte Carlo simulation and Scenario analysis were performed
- Results support logging companies in improving their economic performance

3.1 Introduction

It is commonly accepted how the active management of forests can enhance the liveability of local communities in rural areas both from a socio-economic and environmental perspective, supporting local timber markets and ensuring the provision of several valuable Ecosystem Services, such as protection from natural hazards, recreation and biodiversity (Frank et al., 2015, Fürst et al., 2010). Therefore, in some European countries characterized by low rates of forest exploitation (as is the case in Italy, where the harvest rate is 23% of the growth rate) (Secco et al., 2017), measures and instruments capable of assisting forestry operations could play an important role in supporting the forestry sector at both policy and economic levels. In this context of under-exploitation of forest resources, enhancing the value of the existing coppice forests can represent a consistent opportunity, where these new measures and instruments could be adopted.

Coppice forests, that cover more than 18M ha in Europe (19% of which are in Italy) (Angelini et al., 2013) represent a paradigmatic example of a natural environment which has been profoundly shaped by human intervention. Past management has modified the species composition and structure in order to mainly provide small-sized fuelwood production (Fabbio, 2016). Due to this close relationship with the surrounding human settlements, exploitation of coppices has followed the evolution of society. In Italy, over the last 70 years, these rural areas, where most of these forests are located, have suffered a vast depopulation (Pelleri and Sulli, 1997), that has led to the abandonment of large areas of agricultural land and actively managed forests, allowing secondary woodlands to proliferate (Bätzing et al., 1996, Coppini and Hermanin, 2007). These phenomena, occurring mainly in the Alpine areas, consequently caused a decrease of the ability of forests to cope with natural hazards (Vogt et al., 2006) and reduced the quality and quantity of the harvested timber (Fonti and Giudici, 2001), which is still not sufficient to satisfy national demand (Secco et al., 2017).

In order to support the development of the forestry sector in Italy, many political efforts have been undertaken on both national and regional scales (Quatrini et al., 2017, Marchetti, 2018), with several measures focusing on coppices (Mairota et al., 2016). In addition to these policy measures, the scientific community produced several works addressing this topic, including among others: the benefits deriving from the sustainable active management of coppices studied from the perspective of biodiversity (Mattioli et al., 2016, Müllerová et al., 2015), natural risk reduction (Vogt et al., 2006), logging impacts (Venanzi et al., 2016) and policy solutions (Fabbio, 2016). Nonetheless, this current discussion seems lacking in the evaluation of economic aspects: for this reason, this paper is an attempt to rectify this shortcoming, by establishing a model to analyse the harvesting operations in a coppice forest, in order to define the main factors influencing their economic results.

The selected study area is a chestnut (Castanea sativa L.) coppice located in the Piedmont Region, in the Western Italian Alps. In Italy, this typology of coppice covers almost 1M ha, equal to 27% of all Italian coppices (Angelini et al., 2013) and represents a valuable example of the effects of the different societal trends that influenced forest management over the last decades. In the past, thanks to the many different products that chestnut stands were able to provide (Mariotti et al., 2008), society favoured their presence throughout all the mountainous areas in the country, generating a veritable “Chestnut culture” (Conedera et al., 2004). Then, from the Seventies onwards, the spread of some virulent pathogens, such as Ink Disease (Phytophthora cambivora (Petri) Buisman) and Chestnut Blight (Cryphonectria parasitica (Murrill) Barr.) (Turchetti and Maresi, 2006, Turchetti et al., 2008), and the related physiological problems, such as Ring Shake, limited their use (Macchioni and Pividori, 1996, Fonti et al., 2002). Consequently, these limitations provoked a clear change in their management, shifting from coppice to high forest, or frequently to abandonment (Arnaud et al., 1997, Conedera et al., 2001). From an economic perspective, this change also influenced the profitability of these stands: in fact, the lower value of the achievable wood products, made the economic return of their exploitation uncertain. Currently, chestnut stands are the most common forest type in the Piedmont Region, covering an area of 205,000 hectares, equal to 23% of the forests covering the regional territory (Gottero et al., 2007), and also one of the most common in Italy, but their fate is still uncertain. Therefore, the framework we developed aims to illustrate the potential revenues that can be achieved through a return to the active management of these stands, by providing a reliable economic analysis of the forest harvesting process, taking into consideration both the revenues that can be obtained from the different timber products and the costs associated with logging operations.

To reach this goal, we i) set up a model to evaluate, from an economic perspective, the most likely timber value of a harvest and then tested it on a representative case study located in the Western Italian Alps; ii) assessed the effect and intensity of the variation of the economic and technical factors on the results of the model, through a sensitivity analysis of its parameters and the evaluation of their elasticity; iii) proved the robustness of the results, by applying a reiterative probabilistic analysis based on a Monte Carlo simulation model; and finally, iv) built a scenario analysis with the standard features of the two most common types of private logging companies in the study area, whose characteristics are also well suited to the Italian context. This set of analysis is intended to be employed to compare and analyse the drivers which most profoundly affect the profitability of a harvest in different areas and when adopting different work methods. Moreover, its application with real data from the standard logging companies in the area will also be relevant for entrepreneurs, in order for them to evaluate the management of their logging operations from an economic perspective and to support the definition of the most suitable business strategies to implement their company performance.

3.2 Materials and Method

3.2.1 Case study

The data needed to build the timber value (TV) model was obtained from a case study conducted in the Ormea territory of the Piedmont Region, a small municipality in the Western Italian Alps, 800m above sea level. The analysed chestnut stand is an over-mature coppice stand, with sporadic sycamore (*Acer pseudoplatanus* L.), European ash (*Fraxinus excelsior* L.) and rowan (*Sorbus aucuparia* L.) trees, covering a total area of 0.42 ha. A forest road, suitable for use as a bunching site, where the timber can be collected before its extraction, constitutes the lower boundary of the stand. This area, whose features are consistent with most of the privately-owned coppice forests of the Region (Gottero et al., 2007), can also be considered as an example of the most common state of Italian coppices, where the lack of management has negatively influenced the profitability of the harvest (Moscatelli et al., 2007). In Piedmont, at least 30% of chestnut stands are either abandoned (Manetti et al., 2006) or over-aged and under-exploited (Gasparini and Tabacchi, 2011). Moreover, 89% of these stands in this Region are privately-owned (Gottero et al., 2007), and generally affected by a fragmentation of ownership that negatively influences harvesting activities (Brun et al., 2009). This phenomenon is clearly evident in the statistical data collected from the Italian Statistics Institute (ISTAT), which states that the average harvest area in the Western Alps is equal to 0.46 ha (Istat, 2015), while the area of forest operations in coppice forests, referring to the Piedmont Region, varies from 0.43 to 0.78 ha (Brun et al., 2014a). Therefore, this study can be considered representative of the current forestry situation in the area, securing validity to the results.

The dendrometric data was collected through field surveys with complete callipering of the trees and measurement of a relevant number of tree heights. This data allowed us to employ the Italian Forest National Inventory (IFNI) log rules (Castellani et al., 1984) to estimate the total wood volume of the area, equal to 494 m3/ha.

The stand is an over-aged chestnut coppice stand; since the production of new sprouts for this species is only marginally influenced by the age of the stump (Conedera et al., 2001), the current Regional Forest Law defines specific rules for its management (art. 56; Law 8/r – 2011). In particular, for chestnut stands, no maximum rotation period is defined by law, but a minimum crown cover percentage after harvesting, equal to the 10% of the initial volume, is required. Moreover, it should be noted that pathogens such as ink disease and chestnut blight resulted to be widespread in the stand, negatively influencing the quality of the products.

3.2.2 Timber Value model

To understand how the structural and logistic features of logging companies operating in the Piedmont Region influence the TV of a forestry operation, a model capable of describing and analysing the whole process was developed. TV is the most common measure used to estimate the value of a mature forest stand (Faustmann, 1995, Chang and Gadow, 2010, Navarrete and Bustos, 2013) and is defined as the value of standing timber, as determined from the sales price at the landing location, minus all harvesting costs (Armitage, 1998, Nieuwenhuis, 2000, Amacher et al., 2009). The model we created examines all the positive and negative items in the economics of the logging operation. Regarding timber revenues, the quantities and market values of the assortments were estimated. As for costs, all the segments of the logging operations needed to perform the harvest were analytically considered, and subsequently formalized into a framework able to take into account different harvest types. The TV per cubic meter was then obtained by dividing this value by the extracted wood volume: this value was used as the reference value in this study and in the following analyses. The data acquisition of all the information necessary to build the TV model, e.g. wood volume, achievable products, hourly yields, machinery costs, manpower costs and market prices, is a complex and accurate operation. In fact, all technical and economic data was collected both in the field or by means of a literature review of relevant studies (Picchio et al., 2011, Brun and Blanc, 2017). This data can be divided into three categories: a) ordinary objective data, namely the organization of the logging operations; b) complex objective data, such as the collected and elaborated dendrometric data; c) estimated information, such as the hourly yield and the opportunity costs from the logging company internal data.

3.2.3 Revenues

The main data source concerning timber revenues is the timber market itself, pertaining to both the features of the most common assortments and their price. According to the literature on chestnut timber (Nosenzo, 2007), its products are usually divided into: i) first grade poles, which are straight logs without knots and can be used for natural engineering works; ii) second grade poles, which are mostly straight logs with a limited number of knots that do not affect their technical qualities and are generally used for vineyards and other plantations; and iii) chipping wood for local biomass energy plants. Considering these constraints, the overall amount of the revenues is derived from the product of the n product and its respective price (Eq. (1)).

$$R_{ass} = \sum_{i=1}^{n} p_i \cdot q_i \qquad (1)$$

where R_{ass} is the revenue originated by the trees equal to the sale of the assortment (€) at the landing site; n is the number of the considered assortment; p_i is the price of the i assortment (€ m^{-3}) and q_i is its volume (m^3).

3.2.4 Costs

In order to compute the costs of the harvest, it is first necessary to define the characteristics of the logging operations and their organization, on which the hourly yield depends (Gautam et al., 2014). Despite recent innovations in terms of harvest mechanization and the development of machines that are able to perform different operations over a wide range of conditions (Cavalli, 2008), a traditional organization of harvesting operations still prevails in Piedmont (Picchio et al., 2011). Therefore, a “Short Wood System” was adopted for the harvest. This traditional system, characterized by low mechanization, low budget machinery, often derived from agriculture, and a limited number of employees for each company (Spinelli et al., 2004, Gautam et al., 2014), represents the standard method adopted in the area. In fact, most private companies cannot afford to employ more than two workers, or buy highly mechanized machines, such as harvesters and forwarders (Blanc et al., 2017).

In order to properly compute the costs of the harvest and since different hourly yields and timber volumes were involved, it was necessary to consider the different phases of the logging operations separately, because each phase requires different machinery and manpower. In addition, the wood volume is also influenced by the considered phases. The extracted volume is often lower than the felled one, due to the processing operations, which assume a certain percentage of wood waste. The wood waste value adopted in this study was the 10% of the felled volume, a value consistent with other similar works (Giordano, 1981, Carbone et al., 2013).

According to the Short Wood system employed, the required logging operations are: i) felling and processing, where trees are cut, delimbed, topped and bucked in merchantable lengths; ii) bunching, when poles are transported to the landing site; iii) extraction, when the trunks are hauled to a truck road. The cost of each phase includes machinery and labour costs, where the work hours were computed in consideration of the characteristics of the harvest and of the working strategy adopted (Picchio et al., 2011). It should be pointed out that the number of machinery and labour work hours may not be identical, since some operations can be performed without the need to employ machines. Moreover, as far as the hourly labour costs are concerned, it is important to underline how this amount changes greatly in relation to their source. In this context, two options were defined. The first option is when the workers' wage is considered as external to the company, the price is defined by national agreements, and considered as a full cost for the company (Blanc, 2010). The second option is when it is internal to the company, e.g. because it is performed by the entrepreneur himself or a member of his family, the workers' wage can be evaluated as an opportunity cost (Posnet and Ian, 1996, Brun and Mosso, 2014), that is, the salary of the alternative activity the worker decides to forgo. By contrast, the hourly machinery costs were computed analytically, considering both the fixed costs (capital recovery, interest and depreciation, taxes and insurance) and the variable costs (fuel, lubricant, repair and maintenance costs) that contribute to the final cost amount (Miyata, 1980, Sierra-Pérez et al., in press).

The harvesting costs of the general *i* phase were thus obtained by multiplying the number of hours of work of the *j* machines utilized by their cost per hour, then adding the hours of work of each worker multiplied by the respective unitary costs (2):

$$Cp_i = \sum_{j=1}^{n} q_j \cdot uc_j + \sum_{k=1}^{m} q_k \cdot uc_k \qquad (2)$$

where Cp_i is the cost of a general *i* phase (€); q_j is the number of hours of employment of the general *j* machine (h); uc_j is the average unitary cost of the *j* machine (€ h^{-1}); q_k is the number of hours of employment of the *k* typology of worker (h); uc_k is the average unit cost of the *k* typology of worker (€ h^{-1}); *i* is the number of considered phases; *j* is the number of employed machines and *k* is the number of employed workers.

The number of the employed q_j and q_k factors is influenced by both the wood volume of the harvest and the productivity rate of each phase, namely (3):

$$q = \frac{V}{r} \quad (3)$$

where q is the number of employed factors (h), V is the wood volume processed by a machine in a general *i)* phase (m^3) and r is the productivity rate (m^3 h^{-1}).

The volume is a complex objective datum, and its amount was obtained after processing the dendrometric data using volume tables, whereas the productivity rates were estimated following a literature review (Hippoliti and Fabiano, 1997, Hippoliti and Piegai, 2000, Blanc, 2010). This data was then adapted to the conditions of this study, including environmental adaptations such as slope, road network and terrain roughness, and logistic adaptations such as the extraction distance and harvest intensity, which are determined by features of the harvest site (Accastello and Brun, 2016).

The harvesting costs were computed by summing the amount of each phase, using equation [2]. According to other authors (Carbone, 2008, Picchio et al., 2011), the administrative costs, interest and earnings of the logging company were then added and subsequently evaluated as 5% of the cost of the operations. The TV is the difference between the revenues obtained from the sale of the timber and this sum of costs; the TV per cubic meter is then obtained by dividing this difference by the felled wood volume (4):

$$TV = \frac{R_{ass} - C_{tot}}{\mathrm{V}} \quad (4).$$

where TV is the Timber Value (€·m^{-3}); R_{ass} is the revenues obtained from the sale of the assortments (€); C_{tot} is the overall amount of costs (€) and V is the felled wood volume (m^3). This set of operations constitutes the model to calculate the TV of the harvest. This constitutes the starting point for all the following statistical elaborations, which were performed by employing this model and its results.

3.2.5 The TV of the case study

Once the model had been built, it was used to estimate the TV of the case study. According to the environmental characteristics of the stand and the logistic features of the logging operations, all the values required for the model were measured or estimated, depending on the type of data. A market survey (Piedmont Region personal communication, 2017) was performed to define the type and price of each assortment; the collected data is reported in Table 1.

Table 1: The assortments and their price.

Assortment	**Price (€·m^{-3})**
1st grade poles	70
2nd grade poles	60
Chipping wood	45

Source: market survey, 2016.

The logging operations considered to calculate the harvesting costs were: i) felling and processing with chainsaw; ii) manual bunching along the slope; iii) extraction with a tractor and trailer along the existing road. These operations are summarized in Table 2, which also includes the employed machinery as well as its estimated hourly cost and productivity rate.

Table 2: Description of the features of the logging operations.

Phase	**Adopted technique**	**Productivity (m^3 h^{-1})**	**Employed machine**	**Hourly cost of the machine (€ h^{-1})**
Felling and processing	Processing at the felling site	1.3	Chainsaw	3.10
Bunching	Manual along the slope	1.4	-	0.00
Extraction	Forwarding with trailer	2.9	Tractor, grapple loader and trailer	31.90

The most common private logging company structure in the area was adopted for this evaluation: namely, a craftsman enterprise composed of the entrepreneur and one salaried worker. The hourly wage of the former was estimated as an opportunity cost for the company as 15€ h^{-1}, while the retribution of the latter was defined, according to national agreements, as a cost of 18.63€ h^{-1}. This value was considered the most suitable in relation to the skills required to perform the harvest and the average characteristics of these workers, in terms of years of employment and experience.

3.2.6 Sensitivity analysis

The Sensitivity Analysis (SA) allows the effects on the result to be evaluated in relation to fixed variations of the variables (Grubbs, 1969, Sobol, 1990, Saltelli et al., 2004). This procedure is also known as a "what if" analysis (Himmelblau and Bischoff, 1968), since it evaluates what happens when a default variation of a factor is hypothesized. A specific SA methodology was developed, according to the features of the variables, in order to measure the TV ranges. The results of the performed SA can supply useful information to optimize the decision process of the harvest, to foster the robustness of the decisions that are made and to highlight the main factors that influence the results of the model (Brainard et al., 2006, Navarrete and Bustos, 2013). Consequently, these factors are also those on which it is appropriate to focus during the estimation process (Koller, 1999).

A local SA has been performed in this study. This technique evaluates the effect of each single input variable on the result through a "one factor at a time" approach (Saltelli et al., 2000). The factors were made to vary singularly over a default range of values, while the other input values were kept fixed. The reciprocal independence of the involved variables is a basic element that ensures the reliability of the results, since they cannot influence each other (Zhang et al., 2012). For this reason, a relevant variable such as the fuel price was excluded from the analysis: in fact, since its variation directly influences the hourly costs of machinery, its inclusion would not have maintained the condition of independence of the variables. The SA performed on the TV model included 6 independent variables: 3 related to the economic parameters of the model (namely the hourly costs of the machines and the workers involved), and 3 related to technical parameters (namely the productivity rates of the different logging operations) (Hanewinkel et al., 2014). These parameters were made to vary over specific ranges, as defined in the literature (Hippoliti and Fabiano, 1997, Hippoliti and Piegai, 2000, Blanc, 2010), and then adapted to the conditions of the hypothesized harvest, that is, the conditions that were investigated during the field surveys (Moore et al., 2011). The features of each variable are summarized in Table 3, together with their variation range, which was defined following a literature review (Logan, 2011, Picchio et al., 2011).

Table 3: Input variables involved in the SA.

Variable	Measurement unit	Minimum value	Maximum value
Worker's hourly cost	€ h^{-1}	8.00	25.00
Hourly cost of the chainsaw	€ h^{-1}	2.00	6.00
Hourly cost of the tractor	€ h^{-1}	20.00	45.00
Felling and processing productivity rate	$m^3\ h^{-1}$	0.75	1.75
Bunching productivity rate	$m^3\ h^{-1}$	0.88	1.88
Extraction productivity rate	$m^3\ h^{-1}$	1.25	3.75

The TV variations were then analysed using descriptive parameters to allow a comparison of the considered variables. More specifically, the results were analysed by: i) defining the Break Even Point (BEP) of the variable (Singh and Deshpande, 1982), that is, the value that is able to ensure equilibrium between the revenues and costs (where its position can supply important information about the trend of the variable and the possibility of achieving a profitable harvest); ii) comparing the gradient of the lines, which describes the trend of the relationship between the variables and the results (this elaboration was only possible for the variables that showed a linear trend); iii) calculating the elasticity of this relationship (Pannell, 1997), that is, a parameter that can be used to measure the influence of a variable on the TV (eq. [5]):

$$e = \frac{\Delta Y/Y}{\Delta x/x} \quad [5]$$

where $\Delta Y/Y$ is the variation of the result and $\Delta x/x$ is the variation of the parameter in relation to the value assumed in the estimation. Performing these elaborations on the results of the SA, allowed more information to be obtained about the typology and intensity of the influence of each variable on the TV.

3.2.7 Monte Carlo Simulation

The Monte Carlo Simulation (MCS) is a reiterative analysis of the results of a model in relation to random and simultaneous variations of its independent input factors, in which a normal distribution of the frequencies of the latter is hypothesized (Saltelli et al., 1999). It is commonly adopted to analyse a model and evaluate the robustness of the results (Confalonieri, 2010, Moore et al., 2011). This methodology allows a greater in-depth analysis of the results and the relationship of the model with the input variables, which are investigated together simultaneously. This technique allows the stability of the results of a model, including a stochastic element in its input variables, to be tested in order to simulate the intrinsic uncertainty of the operative conditions. Due to their characteristics of uncertainty, the productivity rates of the logging operations and the average price of the timber products were investigated. Their features were included in the model by defining a random variability, in terms of standard deviation, equal to 10% of the mean value of each considered variable. This analysis was reiterated 10,000 times to simulate the random variation of the variables.

3.2.8 Scenario analysis

A Scenario analysis was the last investigation to be performed on the TV model. It consists of the development of hypothetical conditions of interest, characterized by input variable values chosen by the stakeholder, inserted into the model to study the corresponding result (Saltelli et al., 1999). Therefore, it can be considered as a particular case of sensitivity analysis, since a predetermined modification of the factors is established. The creation of these predefined situations can be useful to understand, for example, which of a group of options is the most suitable for the aims of the stakeholder, in order to support his decision-making processes with objective results supplied by the model (Hoogstra-Klein et al., 2016). Actual data pertaining to the two most represented private forest company typologies in Piedmont were introduced as parameters into the model to build the hypothesized scenarios. The comparison of these scenarios makes it possible to highlight how the structural and logistic features of the logging companies can affect the profitability of the harvest. The data necessary to accurately describe the standard conditions of the private companies operating in the area were obtained from the Regional Register of Forest Companies (http://www.sistemapiemonte.it/aifo), which includes organizational, economic and management information about the enterprises operating in the regional territory (Blanc et al., 2017).

The craftsman logging company, which had previously been considered to estimate the TV, and a logging company owned by a farmer are the two enterprises that were tested in the scenario analysis. These two typologies of entrepreneurs constitute more than 90% of the logging companies operating in Piedmont (Brun et al., 2014b). The differences in these two enterprise structures lie within the adopted machinery and labour costs. As far as the farmer's enterprise is concerned, the agriculture sector is supported by fiscal subsidies distributed to purchase fuel, which consequently costs much less, than fuel sold at the market price (almost 50% less). Moreover, the annual number of hours of machine employment is generally higher than the number reached by craftsman enterprises, leading to a lower hourly incidence of fixed costs. As far as labourer's wages are concerned, workers employed in the agricultural sector have lower salaries than those of qualified craftsman workers, as stated in their respective national agreement. Moreover, the entrepreneur's wages have to be considered differently as it is viewed as an opportunity cost, which is defined by comparing these activities with others they cannot accomplish. While harvesting is the main employment of a craftsman, a farmer usually performs forest activities during the winter, when his agricultural activities are less compelling and profitable. These conditions mean that the farmer should be assigned a lower opportunity cost than the craftsman. Finally, because of the simple technical requirements needed to perform the considered harvest, a delta in terms of productivity rate, cannot be precisely defined for the enterprises. The characteristics of the two considered scenarios are described in Table 4, where the differences between the craftsman enterprise (Scenario 1) and the farmer enterprise (Scenario 2) are listed and compared.

Table 4: Characteristics of the two scenarios.

Cost of item	Scenario 1	Scenario 2	Measurement unit
Entrepreneur's wage (opportunity cost)	15.00	13.00	€ h^{-1}
Employed worker's wage	18.63	14.98	€ h^{-1}
Fuel price (11/2016)	1.06	0.65	€ l^{-1}
Hourly cost of the tractor	31.90	21.30	€ h^{-1}

3.3 Results

3.3.1 Timber value

The revenues derived from the products sale are mainly obtained from the sale of chipping wood, which represents 72% of the wood volume and generates 64% of the revenues. This is because the characteristics of the main species of the stand are not suitable for more profitable utilization, such as construction beams, and pathogens present in the stand had depreciated the value of the majority of the trunks. These conditions are, in fact, quite common in these stands, and only a local energy station, to which the chipping wood can be sold, can make the harvest profitable. In this harvest, 440 trees were felled, and a volume of 187 m^3 of processed wood was obtained, whose sale ensured the enterprise a total revenue of €9,533 (Tab. 5).

Table 5: Assortments and their related revenues.

Assortment	Volume		Revenue	
	m^3	%	€	%
1st choice poles	18.99	10	1329.30	14
2nd choice poles	34.17	18	2050.20	22
Chipping wood	136.74	72	6153.30	64
Total	187.00	100	9532.80	100

The cost of the logging operations were computed according to the methodology illustrated in equations (2) and (3). Administrative costs, interest and earnings of the company were added, and the total cost of the harvest was obtained (Tab. 6).

Table 6: Overall harvesting costs.

Phase	Cost (€)
Felling and processing	3231.68
Bunching	2322.99
Extraction	3218.06
Cost of logging operations	**8772.73**
Administration cost (5%)	438.64
Overall harvesting cost	**9211.37**

The difference between the revenues (€9532.80) and the overall harvesting costs (€9211.37) led to a positive value of €321.43, for a TV of 1.72 € m^{-3}. This demonstrates that the harvest resulted in a positive outcome even though its profit margin is somewhat limited. In this sense, the robustness of the estimation and its sensitivity to the variables that compose it become fundamentally important information to be acquired, as this enables an in-depth evaluation of the achieved economic results.

3.3.2 Sensitivity analysis

The six variables listed in Table 3 were analysed one by one by means of a local SA. The variables were inserted into the model according to the previously described default ranges of variation. Given the different nature of the relationship between the variables and the result of the model, they were divided into two groups. The first group was formed by the 3 variables related to costs. In fact, they all generate a linear relation to the result of the model, which steadily grows as they increase. The trend that these variables originate is shown in Figure 1. The black dots in Figures 1 and 2 represent the values that were assumed in the economic estimation of the hypothesized harvest. As is evident, they are generally close to the negative values of the y-axes, with each variable ensuring wide improvement margins to its performance.

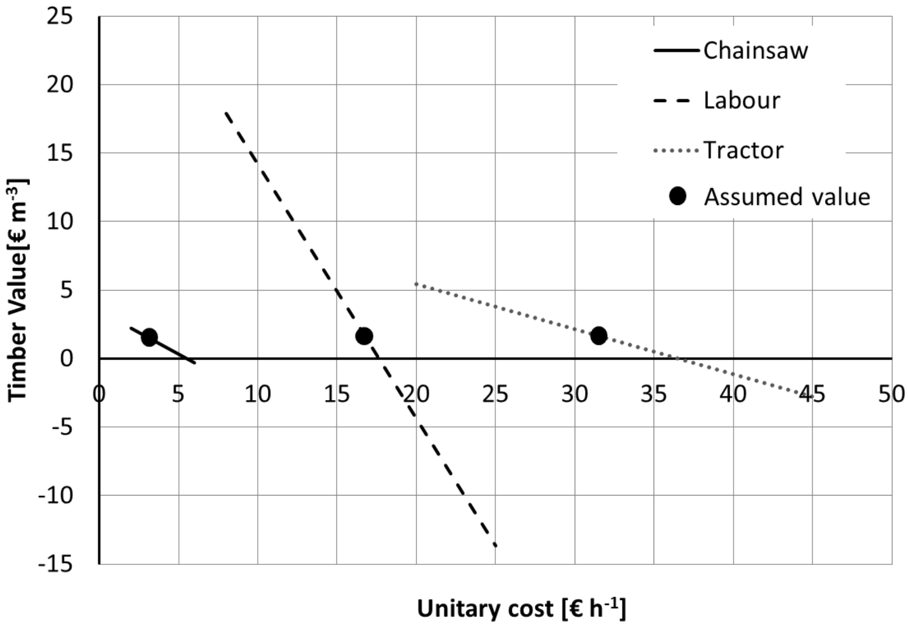

Figure 1: The relationship between the hourly operation costs and the TV.

The graph clearly shows the influence of each variable on the outcome. In fact, there is a noticeable different width of variation and the gradient they assume. The results of Figure 1 are expressed in terms of BEP, gradient and elasticity in Table 7.

Table 7: Analysis of the results achieved with the SA for the three linear variables.

Variable	**Break-even point (€ h^{-1})**	**Gradient**	**Elasticity (%)**
Hourly cost of the chainsaw	4.27	-0.63	-0.7
Hourly cost of the worker	17.22	-1.86	-22.8
Hourly cost of the tractor	36.54	-0.33	-6.8

In relation to the chainsaw hourly cost, it is apparent how its limited width does not allow the TV to vary extensively, even if, due to its gradient, it has already an influence on the profitability of the harvest, making it vary between positive and negative values. An opposite situation can be observed for the labour cost factor, whose high trend slope and wide range influence the TV to a greater extent, and allow very positive (17 € m^{-3}) to very negative (-14 € m^{-3}) monetary results to be reached. Finally, the hourly costs of a tractor represent an average situation, since the effects of its wide range are softened by its low slope, which greatly limits the variations of the TV.

The break-even point, whose values are influenced to a great extent by the range width and the unit of measure of each variable, varies between 4.27 and 36.54 € h^{-1}. The gradient always resulted in negative values, as also evidenced in Fig. 2. Since the slope of the hourly cost of a worker is the lowest negative value (-1.86), it can be hypothesized to have a greater influence on the result, while the hourly cost of a tractor assumes the highest value (-0.63). This situation is confirmed by the elasticity, where the decrease in the TV as a consequence of a 1% growth in the considered variable, ranges from very low (-22.8%) to nearly zero (-0.7%), in relation to the nature of the relationship between the variables and the results. Therefore, we can assume the results depict a close bond between labour costs, which represent 68% of the overall harvesting costs, and the TV of the intervention, as shown by elasticity values higher than 20%.

The variables related to productivity rates, whose trend is shown in Figure 2, are linked to the result of the model by a non-linear relation, in which steady variations of the variables generate a more than proportional increase in the result before the inflection point, and a less than proportional increase after it.

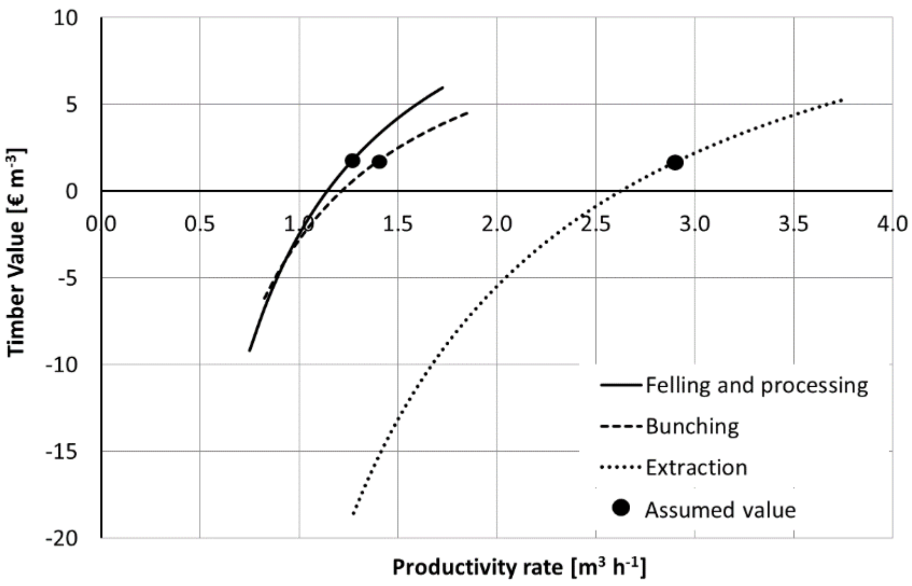

Figure 2: Relationship between productivity rates and TV.

The significant influence of the extraction phase on the final result clearly emerges in Figure 2. In fact, the width of its variation range and the trend of the curve can be seen to clearly affect the TV, which varies from 5 to -18 € m^{-3}. The other two variables regarding the felling, processing and bunching phase, assume a similar trend, whose influence on the TV is limited and mostly ensures positive TV values.

Further analysis was performed in order to quantify the relationship between the variables and the TV, as shown in table 8. The values of the break-even point and the elasticity of the relation are listed for each variable, whereas it was not possible to compute the gradient for them.

Table 8: Analysis of the results achieved through the SA for the three non-linear variables.

Variable	**Break-even point (m^3 h^{-1})**	**Elasticity (%)**
Felling and processing productivity rate	1.14	10.1
Bunching productivity rate	1.21	7.6
Extraction productivity rate	2.63	10.1

The break-even point is very similar for the first two variables, close to 1 m^3 h^{-1}, while the productivity rate of the extraction phase assumes a value of 2.63 m^3 h^{-1}; in any case, it results much lower than the values reported in table 7. Concerning elasticity, the bunching phase has the lowest value, at 7.6%, while the other two factors report the same percentage; all of them have a positive influence on the result, allowing it to increase substantially even with 1% variations.

3.3.3 Monte Carlo simulation

The Monte Carlo simulation took into consideration the simultaneous variation of the three productivity variables of the logging operations and the mean price of the products. While the former were left free to range over a delta of 10% of the standard deviation of their mean value, precise boundaries were fixed for the prices. In fact, the minimum value was set at the price of the least valuable assortment, that is, chipping wood, in order to simulate realistic market conditions, while the maximum was set at the price of the second grade poles. The results of the 10,000 simulations performed are shown in Figure 3, which shows the trend of the function on the cumulated frequency percentage of the TV.

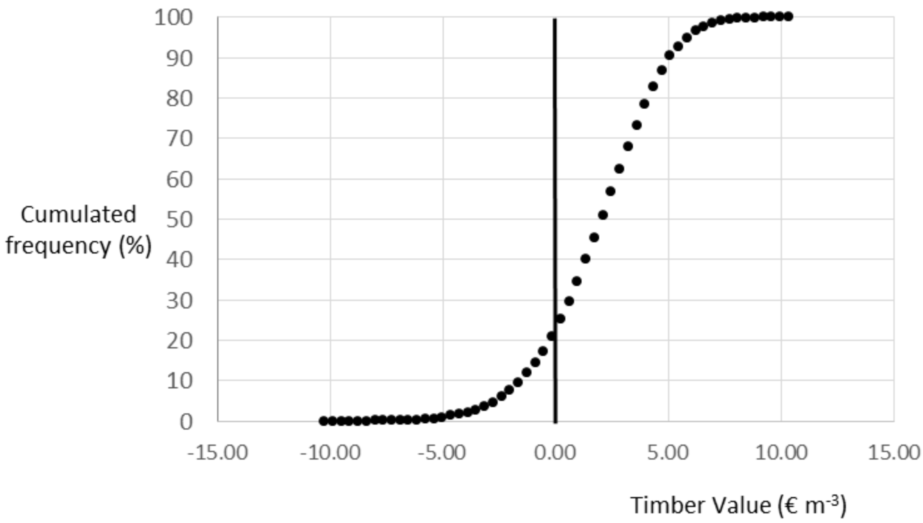

Figure 3: Distribution of the cumulated frequency (F%) of the TV.

As can be noticed, the TV varies from -12 to 10 €m^{-3}, due to the simultaneous variation of the productivity factor, thus confirming its great dependence on the input variables of the model. The graph supports the robustness of the results of our estimation, since the most frequent output is a positive economic result. In the MCS, 68% of the cases led to a profitable harvest.

3.3.4 Scenario analysis

The economic results of the harvest were computed for the two hypothesized scenarios based on the values reported in Table 4, which lists the differences between the two types of enterprises considered (Table 9).

Table 9: Comparison of the main economic parameters achieved for the two scenarios

Scenario	Enterprise typology	Overall unitary harvesting cost (€ m^{-3})	TV (€ m^{-3})
1	Craftsman	49.26	1.72
2	Farmer	35.87	9.31

As shown in table 9, the enterprise run by the farming entrepreneur achieves better results in terms of economic profitability of the harvest, with a lower harvesting cost of 7.59 € m^{-3}. This positive result is also evident when compared to the craftsman, when the TV value is approximately six-fold. This favourable situation, as previously mentioned, is mainly due to the lower hourly costs of the machinery and of labour. Moreover, it can be hypothesized that the results achieved for the farm enterprise are much more robust than the ones represented in Figure 3, since the Monte Carlo simulation performed on the values of scenario 2 led to a probability of obtaining negative economic results close to 0%.

3.4 Discussion and Conclusions

In this study, a model was developed to estimate the Timber Value of a forest harvest in a chestnut stand under standard operative conditions. Each phase of the logging operations has been analysed and included in the model in relation to the standard working protocols of the local companies (Spinelli et al., 2004, Picchio et al., 2011, Gautam et al., 2014). Our case study, characterized by easy accessibility of the stand and organization of the harvest operations, has allowed all the relevant technical and economic factors to be defined and analysed. Even though the analysis only focused on one harvest, given the representativeness of its features, we believe the results of this economic and statistical analysis can be considered to be relevant at Regional and Alpine level and useful to provide some insights related to the management of most of the over-aged chestnut stands in these areas, also thanks to the simulations and to scenario analysis performed. Moreover, since the framework of the model is versatile and able to employ input data that reflects the standard conditions of new study areas (e.g. with further market timber price surveys, or collection of data regarding the most common working organizations and technologies for the area,) it could be used to a great extent for other case studies, allowing the comparison between multiple scenarios.

The approach we adopted to evaluate the TV of the harvest is classic, however, to our knowledge, the manner in which we analysed it from a statistical point of view is innovative and could be adopted in other contexts. Other previous Italian studies (Magagnotti and Spinelli, 2011, Picchio et al., 2011, Spinelli et al., 2012), performed an economic analysis of forest interventions, but the reasons underlying those results were in general little investigated. On the other hand, in this paper the computed TV is a stepping-stone for further analysis that leads to both theoretical and operational insights on their influence on the final result.

More specifically, the sensitivity analysis we conducted, in which all the variables included in our economic model have been considered, enabled the measurement of their influence on the TV (O'Neill et al., 1980, Koller, 1999). This technique has already been adopted in several papers starting from Grubbs (1969) and Sobol (1990) who were the first to focus on this aspect and to define its main framework and rules. More recently, similar research was published by Saltelli (1999) and Saltelli, et al (2004), who focused on describing the different analysis typologies that can be used in relation to the aims of the research and the available data. Similarly, the Monte Carlo simulation also allowed more information to be gained on the profitability of the harvest and on the robustness of our evaluation (Dieter, 2001, Maarit and Kallio, 2010), even though negative economic results were observed for 32% of all the evaluated cases.

At international level, some other studies adopted similar approaches. Among these Whittock et al. (2004) and Oliveira et al. (2012) evaluated the influence of some variables on the incomes derived from plantations by performing a reiterative analysis, while Yoshioka et al. (2002) studied the variation of the cost of biomass production in different harvesting sites. More related to our research are Van Gardingen, et al. (2003), who studied the causes of the variations of the incomes derived from harvesting in relation to different silvicultural management procedures, while other authors have studied the parameters that have the highest influence on the harvest operations, and their effects on productivity (Vangansbeke et al., 2015). This latter work is the most interesting because it adopts a similar approach, combining SA with different scenarios; in our study however, a different scale was considered in order to better reflect the current Italian conditions of the forestry sector and in particular the features of its logging companies.

These aspects were then specifically investigated in the scenario analysis conducted on the data taken from the Regional Register of the Forest Companies, allowing the two most common types of private enterprises in the forest harvest sector to be analysed. This data clearly highlighted the specific features of each of these companies, whose characteristics influence the profitability of the performed harvests to a great extent. In fact, farming enterprises that are able to harvest forest stands clearly emerge to be supported by favourable conditions in terms of labour and fuel costs, which are two elements that do not depend on the personal entrepreneurship skills of the owners. More favourable conditions are also derived from the opportunity of employing the same machines for both the agricultural and forestry activities of these companies, which results in a significant decrease in their fixed costs. On the other hand, this situation entails strong limitations due to the peculiar features of the forestry operations performed in the Alps. While the farmer’s enterprise proved to be very well adapted to a context made of small forest blocks of low quality products situated in favourable orographic conditions, we can assume that on higher slopes with fewer available roads, the lack of professional skills and proper forestry machinery would strongly decrease their economic competitiveness. In those cases, the skills of the craftsman enterprise would represent a decisive aspect in ensuring a positive economic outcome from the harvest.

At policy level, even if this research has illustrated the economic potential ensured by the Chestnut stands of the Italian Alps for harvests on small forest stands, several limitations still remain for this sector. They are mainly related to a weak connection with the wood industry, where the demand of Italian wood products is lacking, or even absent, due to their low quality (Ciccarese et al., 2015), and to the territorial governance guidelines, which over previous years have resulted to be confused and discontinuous (Carbone and Savelli, 2009, Secco et al., 2017). While different governance addresses were pursued in the last decades, causing inefficient resource management, in more recent years, some positive initiatives have addressed the forestry sector, promising to deliver a positive outlook for harvest rates and profitability trends. In the Piedmont Region, an innovative law was passed in 2017 to promote the establishment of associations of forest owners, supporting the shared management of private forest areas (Marandola and Romano, 2012, Beltramo et al., 2018). Similarly, within the application of the last period of the Rural Development Fund, 15 Italian Regions out of 20 funded measures to improve the management of coppiced forests (Quatrini et al., 2017) and a new National Forest Law was recently issued (Marchetti, 2018). Finally, decisive progress was made in the development of management guidelines for coppices in order to reduce the influence of the diseases affecting the chestnut in the achievable assortments (Spinelli et al., 2017, Fabbio, 2016).

Overall, the methodologies included in this study can be considered suitable for our aims and capable of supplying important results to analyse a forest harvest from an economic perspective. The model we built considers all the logging operations and makes it possible to simulate variations of its input factors, whose influence on the TV has been evaluated through SA, MCS and scenario analyses. The latter can be particularly useful to support the evaluation of forest entrepreneurs, since they often operate in very heterogeneous contexts, in which there is a lack of predetermined parameters, and often suffer wide profitability variations due to the variation of single factors. The novelty of this study is represented by both the adopted workflow, combining different economic and statistical analyses, and the study area: to our knowledge, other examples of this kind of analysis in the Alpine area have not yet been undertaken.

In the future, our aim is to further develop the model in order to increase the complexity of the harvests examined so more options can be evaluated and compared. This would include the organization of the logging operations and the machinery involved, allowing more useful information about the profitability of the harvest to be supplied to forest entrepreneurs.

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Conflict of interest statement

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4 An Integrated Approach to Assess Carbon Credit from Improved Forest Management

Journal

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Abstract

Fossil fuel consumption in recent decades has caused the rise of CO_2 concentration in the atmosphere, with negative consequences on the environment and human health. This study develops a methodological framework to quantify carbon credits from carbon-oriented forest management and evaluates the economic sustainability of their sale. Application of the framework to two forest compartments with long-lasting active management in the Western Italian Alps showed the feasibility of the methodology, and provided insights on its replication in other contexts. Particularly, the Carbon-oriented scenario led to a reduction of both the extracted wood volume (10% and 6.5% CASE1 and CASE2 respectively) and Net Present Value (32% and 29%), leading to a carbon credit price of 19.6 € $MgCO_{2eq}^{-1}$ and 44.1 € $MgCO_{2eq}^{-1}$ to counteract these losses.

This work allows us to highlight the factors needed to design and evaluate alternative forest management options while considering the consequences of climate change. Moreover, the hypothesized scenarios include an economic remuneration of the positive externalities provided by sustainable forest management. Finally, the proposed workflow entails undeniable environmental benefits while contrasting climate change, but still looks undesirable in respect to the traditional timber-oriented management in compartments where high quality wood products can be obtained.

Keywords

Bioeconomy; carbon storage assessment; climate change mitigation; forest policy; sustainable forest management

4.1 Introduction

Since the second half of the 20th century, the rapid development of agricultural and industrial activities have produced a strong rise in environmental degradation (Wuebbles et al., 2017). While natural ecosystems provide a wide range of positive externalities, human activity mostly produces negative ones that adversely influence the environment (Duncker et al., 2012). Soon, the basic neoclassical economics assumptions began to be questioned, as did the ability of the market rules to achieve the maximum benefit for human society (Gomez-Baggethun, de Groot, Lomas, & Montes, 2010).

It is now well known that people have to deal with the effects of production processes, known as externalities, still not explicitly included in market dynamics and whose evaluation is problematic (Brun, 2002; Coase, 1960). In recent years, three different methods were developed in order to discourage negative externalities and/or remunerate positive ones (Giupponi, Galassi, & Pettenella, 2009):

- legislation (bans, quotas, fines, tax incentives or dis-incentives, etc.);
- educational methods (communication material, public meetings, etc.);
- market mechanism, like incentives or creation of new markets, payments for ecosystem services (PES), certifications, etc.

At the European level, a remarkable example are the “Greening” measures included in the Common Agricultural Policy to support crop diversification through financial incentives (EU Regulation n. 1307/2013; art. 37). In Italy, a noteworthy example was established by National Law 36/1994, which introduced an additional tax for Water Supply Service Providers in order to finance forestry activity in mountain areas. Additionally, hunting and wild mushroom picking permits should be mentioned as relevant examples of PES (Giupponi et al., 2009).

One of the most troubling aspects of these effects is the increase in the concentration levels of carbon dioxide into the atmosphere (Stern, 2007). Forests play a major role in the global carbon cycle (Shrestha, Stainback, Dwivedi, & Lhotka, 2015), stocking approximately 60% of the carbon fixed in all terrestrial ecosystems (IPCC, 2000) – considering carbon both in plant biomass (branches, foliage, roots) as well as that immobilized in the soil (Canadell & Raupach, 2008). Moreover, forests are involved in about 90% of carbon flows between the atmosphere and the terrestrial ecosystems, therefore play a fundamental role in any climate change mitigation effort. At the same time, since plants have a long life cycle that does not allow them to adapt or escape from rapidly changing environmental conditions (Kolstrom et al., 2011), they are extremely sensitive to anthropogenic climate change. Climate change impacts on forests vary depending on the geographic area considered. In Northern Europe and high-elevation areas, climate change will probably increase woody growth rates, in the short and medium term, due to the lengthening of the growing season (Huber et al., 2014). On the other hand, in the Mediterranean area, water stress is expected to become more intense and frequent, increasing the sensitivity of forests to biotic and abiotic disturbance agents (Lindner et al., 2010) and reducing the ability of trees to stock atmospheric carbon (Pardos, Perez, Calama, Alonso, & Lexer, 2017). In all Earth’s biomes, moreover, climate change is expected to bring about an increase in the frequency of severity of extreme weather and natural disturbance agents (e.g., fire, windstorm), that would result in mortality events that increase sudden carbon emissions into the atmosphere and weaken the mitigation capacity of extant forests (Seidl et al., 2017). In face of such threats, the preservation of resilient and productive forest ecosystems is a major concern and, given this background, there is a strong need to identify silvicultural strategies effective in (a) increasing the climate mitigation potential of global forests, and (b) making the forest more resilient to the adverse effects of climate change (Kalies, Haubensak, & Finkral, 2016). In presence of negative externalities, this kind of management would sometimes requires un-economic decisions, which should be counteracted by incentives (Engel, Pagiola, & Wunder, 2008). To reach this goal, some of the market mechanisms initially designed to preserve environmental integrity have been revamped (Bayon, 2004), e.g. payments for ecosystem services (PES) and markets for ecosystem services (MES), formally codified in the late 1990s and early 2000s (Gomez-Baggethun et al., 2010).

In Europe, after the expiration of the first commitment period of the Kyoto Protocol, and given to the exclusion of forest sinks from the EU Emission Trading Scheme, voluntary carbon trading is now the only option to pursue and reward carbon sequestration by forestry activities. In this context, the aim of the study is to propose an innovative methodological framework to perform an ex ante quantification of carbon credits, and to assess the economic sustainability of a voluntary MES system, applied to two mountain forest compartments in the Italian Alps. To achieve these targets, two different silvicultural scenarios were compared: one continuing current forest management, defined as “business as usual” (BAU), and the other aiming to increase the carbon stock in the forest through dedicated management, defined as “carbon oriented” (CO). These two scenarios were compared from an economic point of view to evaluate whether the expected lower revenue deriving from the CO scenario could be offset by selling carbon credits on the local voluntary carbon market. The current work describes all the methodological steps, compares the results obtained under the two different scenarios, and finally focuses on the method's ability to be replicated.

4.2 Materials and Methods

4.2.1 Study area

The two case studies are public-owned forest compartments, located in the Upper Susa Valley, Western Italian Alps, with a total forest area of 228 (CASE 1) and 504 hectares (CASE 2) respectively (Fig. 1). CASE 1 (N 45.08502 – E 6.98926) mainly consists of European larch (*Larix decidua* Mill.) stands and few Silver fir (*Abies alba* Mill.) stands, at an elevation between 850 and 2000 m a.s.l., the management goal is timber production and hydrogeologic protection. CASE 2 (N 45.01061 – E 6.87569) consists entirely of European larch stands with a productive destination, at an elevation between 1350 and 2300 m a.s.l. Moreover, different features of the achievable wood products characterize the two cases: in CASE 1 the expected assortment is of medium quality, while in CASE 2 high quality ones are more frequent.

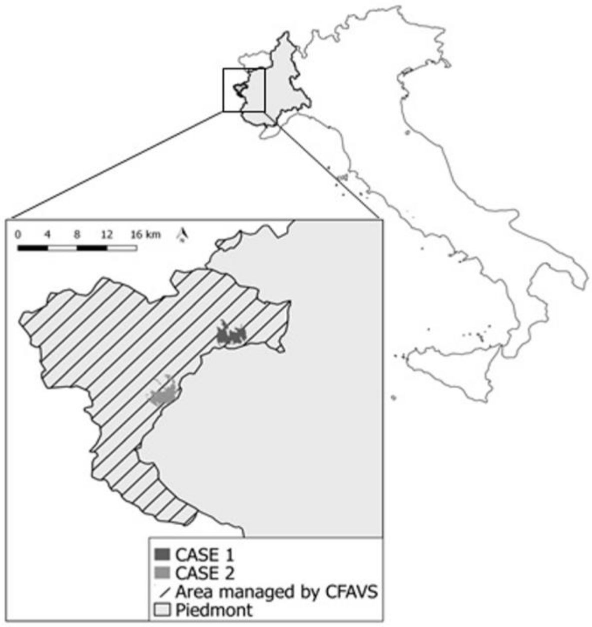

Figure 1: Location of the two study area*s* in Italy and in the upper Susa Valley

Both areas are managed by a consortium of public forest owners, which, since 1953, has been continuously designing and applying decadal Forest Management

Plans (FMP) to the studied forests. The main features of the two case studies are described in Table 1.

Table 1 – Main case study features

Parameters (unit)	CASE 1	CASE 2
Forested area (ha)	228	504
Area reached by road network (ha; %)	59 (26%)	353 (70%)
Altitude (m s.l.m.)	850 - 2000	1350 - 2300
Exposure	North	North-West
Forest category	European Larch (78%); Silver Fir (22%)	European Larch (100%)
Main forest function	Protective-productive	Productive

4.2.2 Scenario building

From a normative point of view, forest legislation In Italy is enacted by Regional lawmakers. In the Piedmont Region, Regional forest Law n. 4/2009 and its related implementation, Regulation n. 8/R (2011), define the allowed array of silvicultural options in forests of different composition and type. More recently, Regional Committee Resolution n. 24-4638/2017 has established the guidelines to implement carbon sequestration through forest management, including quantitative definitions of the baselines upon which carbon credits are computed (Vacchiano, Berretti, Romano, & Motta, 2018).

In order to evaluate the economic consequences of the shift from a traditional, productive silviculture to a management oriented to carbon sequestration, we built two scenarios and compared the effects implied by their different management options. This technique allows us to hypothesize, through quantitative or qualitative assumptions, the results of variations in some influencing factors called drivers of change (Walz et al., 2007). Moreover, the adoption of scenarios can support and address the decisional processes by supplying credible, salient and legitimate information to forest managers and decision makers (Rounsevell & Metzger, 2010). Therefore, we built two scenarios whose consequences have been tested over a period of 30 years, which corresponds to the minimum time required by the Regional guidelines in order to be credited for a Carbon-Oriented management commitment, and it is equal to the duration of two FMPs.

The first scenario developed is the BAU, which models forest dynamics under the continuation of management goals and harvest parameters currently adopted. Its objective is to maximize the revenues deriving from timber sales, while complying the regional forest legislation. Harvest intensities, the driver under BAU scenario, were obtained for the two main forest species in the study area from an elaboration of regional data (IPLA, 2003) and from historical information included in the most recent FMP for the area. This scenario represents the benchmark to compare the consequences of a shift to carbon-oriented management.

The CO scenario describes an alternative but plausible development of the current situation. The main difference with BAU is represented by the reduction of harvest intensity in comparison to the standard situation. This reduction was quantified working together with local experts, trying to identify the best compromise between the effectiveness of the forest cut and biomass stocking, and complying with harvest intensities suggested for each forest species by the Regional guidelines for carbon credits. Indeed the hypothesized CO management of the two compartments corresponds to a micro-project (having an area <1000ha) of "improved forest management" (Molteni & Blanchard, 2013). This practice consists in an increase of carbon sequestration and/or a decrease of emissions, compared to a conventional one.

4.2.3 Scenario modelling

The two scenarios were tested on both study areas. The effects of their adoption have been simulated employing four different numerical models, each of them focused on analyzing a different aspect of the workflow. Namely, the adopted models are:

- the "Carbon Budget Model" of the Canadian Forest Sector, CBM (Kurz et al., 2009), an empirical area-based forest growth simulator which employs dendrometric and auxometric data to simulate forest growth based on expected harvests;
- the "Spatial Based Economic Model", SEM (Accastello, Brun, & Borgogno-Mondino, 2017), for the economic evaluation of the forest cuts under the orographic, environmental and logistic constraints of the harvested area;
- the "Yet Another Forest Optimizer", YAFO (Hartl, Hahn, & Knoke, 2013), which, from the results of the previous models, optimizes the management schedule of the forest stand by maximizing revenues;
- the carbon accounting models from the (Carbomark Project, 2011), which adopt a carbon pools-based methodology to estimate the carbon credits generated by a dedicated carbon-oriented forest management. In

this study, only aboveground live carbon pools were considered, as per the extant Regional guidelines.

The harmonized use of these models allowed us to evaluate the Break Even Price (BEP) of the achievable carbon credits, that is the selling price of the carbon credit generated by the CO scenario able to offset the lost revenues derived from the reduced harvest intensity (Figure 2).

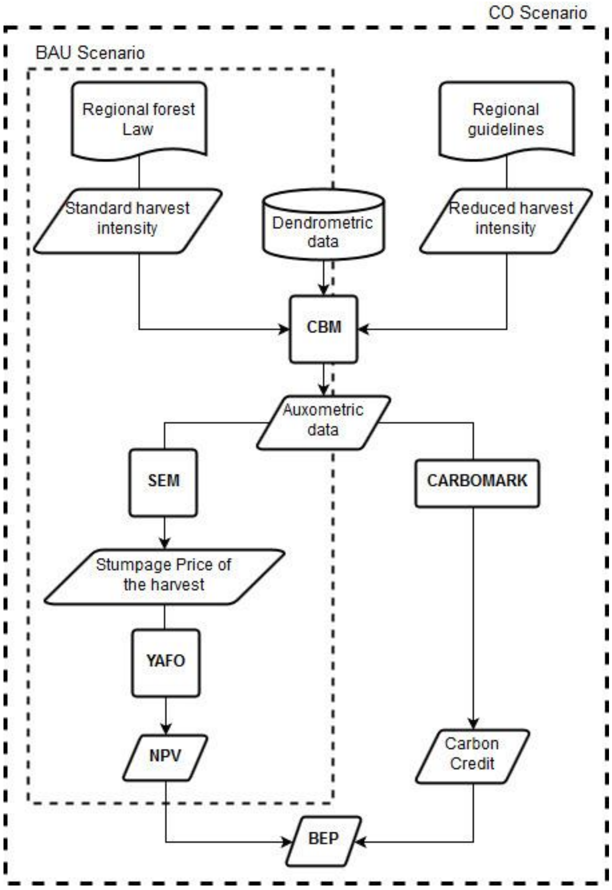

Figure 2: Framework of the harmonization scenarios

4.2.4 Forest measurements

To filter out forests not available for wood supply (i.e., where management is not possible), we included in all subsequent analyses only forested areas reached by the existing road network, or reachable after the forest road improvements planned by the current FMP. In fact, according to the Regional guidelines, only these areas are eligible for CO management.

After this selection, the remaining areas were divided in smaller parts, called cutblocks, with common characteristics in terms of forest typology, past management and structure (Armitage, 1998; Bagnaresi, Bernetti, Cantiani, & Hellrigl, 1986). Cutblocks were described quantitatively by their forested area and by the results of a tree sampling carried out during the drafting of the FMP. One angle-count sampling point was randomly established in each cutblock; for all trees tallied, species, diameter at beast height (dbh), and basal area were recorded. Tree height and 10-year radial increment was also measured for a sub-sample of 3-6 trees per plot belonging to different dbh classes. For every cutblock, the following dendrometric variables were available: dominant species, site productivity (according to a three-class categorical system based on expert guess), basal area, merchantable overbark tree volume (computed using locally available volume equations), 10-year current increment (computed from tree growth samples), and stand age (from previous FMP data – all stands were even-aged).

4.2.5 Model implementation

The first step of the simulation workflow was to project the growth of each cutblock in the next 30 years under the BAU and CO scenarios (only for forests available for wood supply). CBM was initialized with cutblock species, age, volume and area, and with a set of volume-age growth curves for every combination of species, study area, and site productivity class. These curves represent the merchantable aboveground volume in the absence of natural disturbances and management practices. Growth curves were fitted by (a) modeling 10-year increment as a function of current volume and age (third-degree polynomial spline); (b) calculating volume between age 0 and 250 as the cumulative sum of the modeled increments; (c) fitting a second-degree polynomial function of calculated volume over age; and (d) reducing growth curves by an amount correspondent to natural mortality, which we assumed to be 2%, 0.01%, 0.3%, and 0.05% respectively at ages 0-10, 11-40, 41-100, and 101-250. The harvest activity to be modeled was determined by the specific provisions of the BAU and CO scenarios for every forest type represented in the cutblocks, and modeled in terms of percent removal of aboveground biomass. For every combination of study area and scenario, seven instances of CBM were run, each with a different time of harvest, ranging from year 0 to year 30 with a 5-year interval, in order to produce the data for subsequent economic optimization. This allowed measuring both the generated wood products (Raymer, Gobakken, Solberg, Hoen, & Bergseng, 2009) and the sequestered carbon pools, by using species-specific conversion factors. To build the auxiliary files needed by CBM (archive index of parameter tables; geographic boundaries of climatic units for carbon pool initialization) we used the European calibration of CBM developed by the Joint Research Centre of the European Commission (Pilli, 2017). In this work, version 1.2 of CBM was used.

Then, for each feasible harvest, SEM was used to compute its stumpage price (Chang, 1983; Sessions & Sessions, 1992; Torres, Perez, Robredo, & Belda, 2016), i.e., the difference between income from the sale of harvested wood (Accastello & Brun, 2016) and harvest costs. The latter were evaluated by combining the hourly costs of machinery and labor with the productivity rates of the felling, processing, and extracting phases of the harvest (Miyata, 1980; Sierra-Pérez, García-Pérez, Blanc, Boschmonart-Rives, & Gabarrell, 2018). To evaluate the harvest productivities we computed a Block Exploitation Aptitude index for each block (Accastello et al., 2017). This index sums up the orographic, environmental and logistic features of a forest stand to evaluate its suitability to be harvested. Then, index values were linearly related to a range of productivity rates derived from the literature of alpine forestry (Akay, 2005; Gilanipoor, Najafi, & Heshmat Alvaezin, 2012; Koutsianitis & Tsioras, 2017; Mologni, Grigolato, & Cavalli, 2016; Sanchez-Garcia, Canga, Tolosana, & Majada, 2016) to obtain a specific value of productivity.

Once the harvest intensity and stumpage prices were known for all possible five-year period in which harvest could take place, the YAFO model was used to optimize forest management over a 30 years span. This model defines the best period to harvest for each block, maximizing the stumpage price achievable from it (Hahn et al., 2014). Therefore, its results are relevant from both a planning and an economic perspective, since the sum of the discounted stumpage prices constitutes the Net Present Value of the whole compartment over the 30 years of management, calculated by using a 2% interest rate. Since this methodology was employed under both scenarios, the difference in NPV resulting from different harvest intensities between BAU and CO will show the economic consequences of shifting towards a carbon-oriented management .

Finally, the increase of standing wood biomass due to the adoption of CO management was used to calculate the marketable carbon credits. The methodology quantifies the tonnes of equivalent carbon dioxide (t_{CO2eq}), and it is consistent with ISO 14064-2 and with Verified Carbon Standard VCS (3GreenTree, 2013).

Due to the short time span considered and the significant degree of uncertainty of this field measures, we limited our analysis to the carbon included in the living above-ground biomass pool by trees, disregarding the other carbon sinks, i.e., understory biomass, dead organic matter, litter, living below-ground biomass, and soil. The estimations are therefore to be considered as conservative. In order to calculate the credits resulting from improved forest management (CMg_{CO2eq}) we used the following equation, formerly proposed under the Carbomark project

(Carbomark Project, 2011), and here amended accordingly to the context of our study (Eq. 1):

$$CMg_{CO2eq} = \left[\sum_{i=1}^{n}\left(V_{b,i} - V_{c,i}\right) \times A\right] \times BEF \times 0.5 \times \frac{44}{12} \quad \text{[Eq. 1]}$$

where:

- CMg_{CO2eq} = Carbon credit produced [Mg_{CO2eq}]
- $V_{b,i}$ = felled volume per unit area of the *i* stand in the BAU scenario [m^3 ha^{-1}]
- $V_{c,i}$ = felled volume per unit area of the *i* stand in the CO scenario [m^3 ha^{-1}]
- A = area of the *i* block [ha]
- BEF = biomass expansion factor, in order to obtain dry matter mass from the stem volume (Federici, Vitullo, Tulipano, De Lauretis, & Seufert, 2008), [Mg m^{-3}]
- 0.5 = conversion coefficient to obtain the amount of carbon from dry matter mass [MgC t^{-1}]
- 44/12 = Conversion coefficient to transform the carbon amount in CO_{2eq} [MgCO_{2eq} MgC^{-1}]

In such evaluations a safety margin should be provided, called a buffer, to account for possible extra carbon emissions due to natural disturbances (e.g., fire) during the accounting period. We calculated this value on the basis of the average yearly disturbance risk (i.e., ratio of area disturbed to total forest area) reported for similar forest types in a nearby mountain region, amounting to 0.3% $year^{-1}$ (Valle d'Aosta Autonomous Region & Piedmont Region, 2011); therefore the total credits were reduced by 9% for the considered time span.

Finally, we computed the BEP using the following equation (Eq. 2):

$$BEP = \frac{\Delta\, NPV}{\Delta\, CMg_{CO2eq}} \qquad \text{[Eq. 2]}$$

where:

- BEP = Break Even Price of the achievable carbon credits [€ tCO_{2eq}^{-1}]
- Δ NPV = difference between the NPV under the BAU scenario and the one under the CO scenario [€];

- $\Delta\, CMg_{CO2eq}$ = difference between the result of equation 1 under the BAU and the CO scenario [$MgCO_{2eq}$]

It is necessary to specify that the estimated BEP values are gross of transaction costs, which are implied in the sale of the obtained carbon credits. This procedure is due to the remarkable uncertainty about brokering costs; nevertheless, it is consistent with the experience of the ForCredit project (Molteni & Blanchard, 2013), where transaction costs were fully supported by the purchasers.

4.3 Results

The integration of the four adopted models allowed us to achieve our working goals. CBM modelled forest growth, computed different options for harvesting over the period of 30 years that was considered, and provided the necessary inputs to determine the stocked carbon pools. As expected, the CO scenario led to an overall reduction of harvest intensity and of the extracted volumes. In particular, the mean reduction amounted to 10% in CASE1 and to 6.5% in CASE2. The subsequent application of SEM and YAFO allowed us to assess economic results (Table 2). From an economic point of view, in both case studies the CO scenario is less profitable than the BAU: NPV decreased by 32% for the first area and by 29% for the second one. Moreover, due to the effects of temporal harvest optimization, over the 30-year period the felled volumes decreased by 19% in CASE1 and by 15% in CASE2.

This translated into a potential loss of revenue for the forest owners of about 32,500 € in CASE1 and up to 386,300 € in CASE2. Such a difference derives from both the quality of the achievable assortments and the eligible forest area for CO management, which is more than five times greater in CASE2 than in CASE1.

Table 2: Harvest data and related economic results

Parameters	Unit	CASE 1 BAU Scenario	CASE 1 CO Scenario	CASE 1 CO-BAU (%)	CASE 2 BAU Scenario	CASE 2 CO Scenario	CASE 2 CO-BAU (%)
Total harvest	m^3	7 128	5 777	-19.0%	39 052	33 255	-14.8%
Unitary harvest	$m^3\ ha^{-1}$	120	97		111	94	
NPV	€	100 912	68 429	-32.2%	1 333 621	947 316	-29.0%

The shift from BAU to CO generated an increase in stocked aboveground of +10% for CASE1 and +8% in CASE2, producing a carbon credit of 28 and 25 $t_{CO2eq}\ ha^{-1}$ respectively (Table 3). The carbon price needed to offset the loss of productivity was 20 and 44 € t_{CO2eq}^{-1}, respectively.

Table 3: Evaluation of the produced carbon credits and their related selling price

Parameters	Unit	CASE 1			CASE 2		
		BAU Scenario	CO Scenario	CO-BAU (%)	BAU Scenario	CO Scenario	CO-BAU (%)
Sequestered carbon	Mg_{CO2eq}	16628	18289	+10.0%	107568	116319	+8.1%
Credit produced	Mg_{CO2eq}	-	1661		-	8751	
Single credits	Mg_{CO2eq} ha^{-1}		28			25	
BEP	€ Mg_{CO2eq}^{-1}		**19.6**			**44.1**	

4.4 Discussion and Conclusions

The consequences of human induced climate change are expected to increase in the near future. Therefore, a forest management oriented towards the mitigation of this phenomenon is strongly recommended (Clark, Skowronski, & Gallagher, 2015; Elkin et al., 2013; Stern, 2007). To this extent, the inclusion of positive externalities generated by sustainable forest management into market mechanisms seems a desirable and feasible goal. Therefore, the adoption of economic instruments that support climate change mitigation, such as payments for ecosystem services and markets for environmental services (Gomez-Baggethun et al., 2010), is of utmost importance. However, in order to make such experiences valid and effective, a sound regulatory structure is required (Engel et al., 2008; Muradian, Corbera, Pascual, Kosoy, & May, 2010). For this reason, the implementation of these instruments cannot be separated from a clear institutional interest. The voluntary carbon credit Guidelines produced by the Piedmont Region administration seem to be consistent with such need, aiming to foster a voluntary market of carbon credits obtained from improved forest management practices. In accordance with the current regulatory framework, this study has put forward a set of tools and a replicable workflow to evaluate the economic viability of CO forest management, which was tested in two forest compartments which have been continuously managed for decades.

The models used for the optimization of forest management have showed complementary and integrated characteristics. Forest dynamics simulated by CBM over the next 30 years, and the corresponding output of carbon accounting models, have been positively evaluated by local forest experts. The economic results produced by SEM and suggested that CO management could represent a viable alternative to business-as-usual management activities. However, the BEP showed high variability between the two study cases: while in CASE1 it amounted to around 20 € t_{CO2eq}^{-1}, in CASE2 it was more than twice that amount. Consequently, in the first case the adoption of CO management can be deemed economically viable, since the quotation of the credits on the Italian voluntary market in 2016 was 28.5 € t_{CO2eq}^{-1} (Brotto et al., 2016). On the other hand, in CASE2, where ordinary management is more profitable due to the higher quality of woody assortments, BEP rose to 44 € t_{CO2eq}^{-1}. While the forest owner was willing to undertake a Carbon Oriented scenario, the current carbon quotation was not able to balance the forecasted loss of income.

Hence, we suggest that a shift towards CO management could be of interest where the forest produces average -to low- quality assortments, a common situation in Italy (Accastello, Blanc, Mosso, & Brun, 2018; Pettenella & Romano, 2010). On the other hand, where the stands provide more valuable products, the high BEP of the credits will make them much harder to sell on the market. Furthermore, CO management is not to be pursued where the provision of other non-marketable ecosystem services of high importance (protected areas; direct protection forests) is the main goal of forest and land management.

It should not be forgotten that the current management is already sustainable from the environmental point of view, as the overall harvest per year amounts to <40% of the available increment. Nevertheless, a further increase of carbon stocks in aboveground (and belowground) pools, achievable under CO management, should provide even more benefits to contrast climate change on a global scale (Khanal et al., 2017).

However, attention should be paid to the social spillovers that CO management may imply. While forest owners could compensate lower revenues by selling the carbon credits, unwanted negative effect may arise in the local timber sector due to the lower felled volumes put onto the market. Even though the forest sector represents a very limited portion of the economy in southern European countries (Bernetti, Casini, & Marinelli, 1994), such a reduction would be noticeable at the local level, leading for example to increase foreign imports from unsustainably harvest wood, or to a decrease in the employment rate, and finally have consequences on territorial management. Another critical issue related to carbon credit sales consists in the considerable lack of transparency in the voluntary credits market, especially regarding the permanence of project conditions and management commitments over the planned 30-year period. Moreover, the carbon credit trading that has taken place in recent years appears to be dominated by negotiation between private parties rather than taking the shape of an actual market, as reported by Molteni et al. (2013) and Brotto et al (2016). To date in Italy, a steady offer of carbon credits is lacking, and this negatively influences the demand as well.

However, the recent issuing of a new national forest law that encourages widespread forest planning, and the duties on LULUCF reporting implied by the Paris Agreement, suggest that voluntary carbon markets from local forest management may play a more important role in the next future. Since carbon credits can be certified only in presence of a forest planning document, guidelines on how to implement existing plans with carbon accounting (both biophysical and economic estimates) will be needed. Plan and guidelines may also help highlighting synergies and tradeoffs between carbon stocking and other regulatory ecosystem services provided by the forest, such as biodiversity or hydrogeologic protection, supporting their prioritization by the forest manager.

In summary, with this study we were able to demonstrate the steps required order to design and evaluate two alternative scenarios of active forest management from an economic perspective. Although the conditions studied are very specific (coniferous forests in alpine mountain range, with long-established management plans), the premises for the repetition of these preliminary evaluations in other contexts are concrete.

The proposed methodological framework can be run in any forested area, provided that the user can parameterize them with locally valid growth equations (taken from yield tables, forest inventories, or process-based growth models) and initialize them with the necessary input (forest composition, age, and volume). With such simulation approach, carbon fluxes can be quantified ex ante (i.e., before the commitment to generate them starts) and carbon credits obtained by comparing forest dynamics under the planned management versus those under business as usual (or other accepted baseline management), as the additionality criterion requires. On the other hand, the economic optimization allowed us to assess the economic viability of carbon-oriented management, by choosing the time of management so as to maximize revenues.

The model integration framework suggested herein has proved to be effective, both from the methodological and the results side, thus it may become a useful tool for forest managers interested in operating on the voluntary carbon credit market.

The innovation contained by our analysis lies mainly in linking a forest growth and carbon simulator with an economic optimization model, which allowed us to go beyond a static or simplistic quantification of carbon sequestration, to embrace a full assessment of carbon fluxes under different management alternatives. Further implementations of the modelling framework will mostly rely on the additional assessment and valuation of carbon stocked in harvested woody products, which will have to be accounted for under the new Paris regulations, so as to be able to evaluate potential trade-offs between managing the forest to increase live aboveground carbon versus managing to extract long-lived woody assortments which may store carbon for an even longer time.

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5 ASFORESEE: a Harmonised Model for Economic Evaluation of Forests Protection Service against Rockfall

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Abstract

Gravitational hazards, such as rockfall, constitute a major risk in mountainous areas, threatening dwellers, goods, and infrastructures, and ultimately posing a challenge to their development. Ecosystem-based solutions for Disaster Risk Reduction (Eco-DRR), such as protection forests, can play a significant role in mitigating these risks by integrating the protective structures currently adopted, which are often costly and could entail higher environmental impacts. This study develops an economic model called ASFORESEE (Alpine Space FORest Ecosystem Services Economic Evaluation) to assess the protective service forests provide against rockfall within a standardized framework adopting a precautionary approach. The Replacement Cost approach was adopted, measuring the protection effectiveness, the need for protection of the stakeholders and defining a harmonized method for the design of the defensive structures. Applying the model to a case study in the Italian Alps, the results show the forest has a relevant protective effect able to fulfil the stakeholders' needs, with a value of 30,440€ ha^{-1}, equal to 950€ ha^{-1} $year^{-1}$, within the 25-year timespan considered. ASFORESEE could feasibly be adopted in other mountainous contexts, due to its harmonized structure reliant on minimal assumptions. Its adoption would foster the acknowledgment of the forest role and to further support the inclusion of Eco-DRR in local risk management plans.

Keywords

alpine space; ecosystem-based solutions for Disaster Risk Reduction (Eco-DRR); ecosystem services; protection forest; replacement cost; gravitational hazards; natural hazards

5.1 Introduction

The Alpine Region is inhabited by approximately 14 million people, unevenly distributed within its boundaries, making it one of the most densely populated mountainous areas of the world (Alpine Convention 2015). In this area, and likewise other mountainous regions of Europe, in a perspective of increasing anthropic pressure and more intense and frequent natural hazards triggered by climate change (UNISDR 2015; Howard and Sterner 2017), there is a rising need for protection from these threats. It is a given certainty that in the future it will be hardly possible to avoid the presence of elements, such as people, goods, infrastructures, and productive activities, located in areas subject to natural disasters (EEA 2010).

In the Alps, two main strategies to ensure satisfactory risk mitigation from natural hazards have traditionally been adopted: the construction of technical defense measures such as barriers, rockfall nets and dams; or the management of the Alpine ecosystems, e.g. mountain forests, to maintain or improve the protection (Motta and Haudemand 2000; Keiler and Fuchs 2018). This service, included in regulation Ecosystem Services (ES), consists of the mitigation of hazards triggered by gravity, such as rockfall, avalanches, and shallow landslides, thanks to the combined effect of superficial stabilization (e.g., of snow cover and rock cliffs) and the impediment created by the trunks of such forests (MA 2003). In the modern era, as the anthropic pressure has risen to its current levels, the first approach, based on artificial structures, has clearly become predominant (Keiler and Fuchs 2018). Nonetheless, the adoption of such measures implies several drawbacks, such as high maintenance costs, visual impact and alteration of natural environments (Holub and Hübl 2008; Keiler and Fuchs 2018). Conversely, the capacity of Ecosystem-based solutions for Disaster Risk Reduction (Eco-DRR) to provide affordable, low-impact, and multifunctional solutions to risk mitigation is well known and has already been modelled in a number of studies (Rimböck et al. 2014; Miura et al. 2015; Dupire et al. 2016; Moos et al. 2018). Hence, recognizing the direct protective service provided by mountain forests to assets and people in local risk management strategies and in decision-making processes is of paramount importance to achieve a resilient and cost-effective protection (Grilli et al. 2015; Onuma and Tsuge 2018). In this respect, the potential role of Eco-DRR has been underlined by several policy documents of international relevance (EC 2013; Faivre et al. 2018).

A reliable assessment of this service represents the cornerstone to give value to Eco-DRR and integrate them into risk management strategies, thus avoiding disproportionate public expenses in building defensive facilities (Fidej et al. 2015). Such an assessment can be performed in several alternative ways, utilizing both qualitative and quantitative methods, for instance, multi-criteria analysis, and expressed in different alternative measurement units. Among the latter, monetary evaluations stand out for their ability to translate environmental functions into economic terms, favoring their understanding by policy and decision makers. Notwithstanding the important ethical and methodological issues in reducing such complex environmental services into monetary values (Spangenberg and Settele 2010; Farley and Voinov 2016), these methods still remain the most effective instrument to measure the value of an ES, that would otherwise be overlooked. Consequently, their evaluation could help draw attention to their management and thus support the integration of Eco-DRR into risk management strategies (Grêt-Regamey and Kytzia 2007; Daily et al. 2009). Several studies have already been conducted, mainly in the alpine space, concerning the economic evaluation of the protective service of forests against the different natural hazards influenced by its presence (Bianchi et al. 2018). Among those, the study from Notaro and Paletto (Notaro and Paletto 2004) represents a seminal example of the application of the Replacement Cost approach at landscape level. There, the methodological limitations of upscaling this method to areas larger than single protection forest stands were bypassed by involving a focus group of experts, in order to evaluate the influence of several forest features in providing protection from natural hazards in general. This study was followed by several other researches carried out in Italy, Switzerland, and France, where this approach was applied at forest stand-level (Cahen 2010; Dupire et al. 2016; Bianchi et al. 2018). Conversely, a more limited number of studies adopted other indirect evaluation methods, such as the Avoided Damages method, in which the protection service of a forest is valued in relation to the damages it prevents (Teich and Bebi 2009; Moos et al. 2018). The majority of these studies focused on avalanche protection, narrowly adopting a stand-level focus(Teich and Bebi 2009; Cahen 2010). Other studies instead emphasized the role of forests against other hazards, as shallow landslides (Vergani et al. 2017) and debris flows (Fidej et al. 2015), but without providing a monetary evaluation of this service. Finally, direct methods of elicitation of stakeholders' beliefs and willingness to pay were seldom adopted for such evaluations (Olschewski et al. 2012). Additionally, their replicability is low, since the results are the consequence of the relation between the considered protection forest stand and its beneficiaries. In a nutshell, these studies showed a large variability of both the available methods and the units of measure of the results, which were alternatively presented as values, i.e. a lump sum of money, or incomes, often expressed as money ha^{-1} $year^{-1}$ (Bianchi et al. 2018). This heterogeneity leads to a general lack of consensus on the most suitable methodology to be applied in the evaluation of this ES, undermining its wider adoption in a standardized and replicable way.

In consideration of the lack of the evaluations presented in these studies , the aim of this research is to develop a model for the economic evaluation of the protection forest service, harmonizing data on forest stands with technical and economic parameters into a replicable and standardized framework, able to consider the societal needs of livability and safety. The only natural hazard here considered is rockfall, a typology of landslide confined to the detachment of individual rocks (L.K.A. Dorren and Berger 2006), which, despite its high specificity, constitutes a relevant issue for mountainous areas (Luuk K.A. Dorren 2003). Moreover, as an additional objective, this model should be suitable to be adopted by decision makers and practitioners of Eco-DRR in any mountainous region affected by rockfall, in order to standardize the assessment process and attribute value to protective forests, supplying easily understandable monetary information. This economic model, developed within the INTERREG Alpine Space project "ROCKtheALPs" is named ASFORESEE (Alpine Space FORest Ecosystem Services Economic Evaluation) and it is based on the traditional Replacement Cost approach, which resulted to be the most suitable method in terms of potential harmonization of the approach and of achievement of effective outputs, as explained above. Its adoption in estimating the regulation ES of a forest is well documented (Farber, Costanza, and Wilson 2002), even if limited to only one of the many services that forests provide (de Groot et al. 2010).

The paper is structured as follows: Section 2.1 describes the framework of the model and its components. Then, in the following sections the demand for protection by stakeholders (Section 2.2), the technical data on forest effectiveness (Section 2.5), protective facilities (Section 2.4), forest management (Section 2.5) and the methodology adopted for the economic evaluation (Section 2.6) are extensively explained. In the Results (Section 3), the model is applied to a selected case study, in order to test it on a real rockfall event and evaluate the protection ES supplied by the forest. Finally, findings, limitations, and possible future developments of ASFORESEE are discussed in the Discussion and Conclusion (Section 4) that complete the study.

5.2 Materials and Methods

5.2.1 Model Framework

The ASFORESEE evaluation model is based on the Replacement Cost approach, one of the most suitable methods to assess regulation and protective ES (Haynes-Young and Potschin 2012) and whose adoption in mountainous areas is well documented (Luuk K.A. Dorren 2003; de Groot et al. 2010; Bianchi et al. 2018). The approach assumes that the value of the protective service ensured by forests against rockfall is equal to the expenditures that would be potentially incurred to reproduce the same service by artificial means. Its application is subject to three requisites: (i) the artificial structure hypothesized to replace the forest must have the same effectiveness; (ii) it must be the least costly option available on the market, notwithstanding the first requisite; (iii) there must be an interest of the stakeholders benefiting the service, to maintain and replace it, when lacking (Bockstael et al. 2000). This approach also presents some limitations. Among others, when dealing with landscape or regional scale evaluations, the uncertainties due to the assumptions needed to adopt the method are high (Bianchi et al. 2018). Moreover, this approach is generally not able to emphasize the importance of the different elements at risk, since it focuses on the forest rather than on the objects of the protection. Moreover, only one of the several ES provided by forests is considered, excluding other relevant regulation, cultural and provisioning ES. Nonetheless, given the aim of the study to provide a replicable model based on a standardized workflow and based on the available literature and empirical evidences, this approach resulted to be the most suitable.

In consideration of the interactions between rockfall events, forest, hypothetical defensive facilities and expenses related to these elements, the model requires several technical, economic, and modelling inputs to be combined. The overall conceptual framework of ASFORESEE, depicting the logical flow underlying its structure in shown in Figure 1.

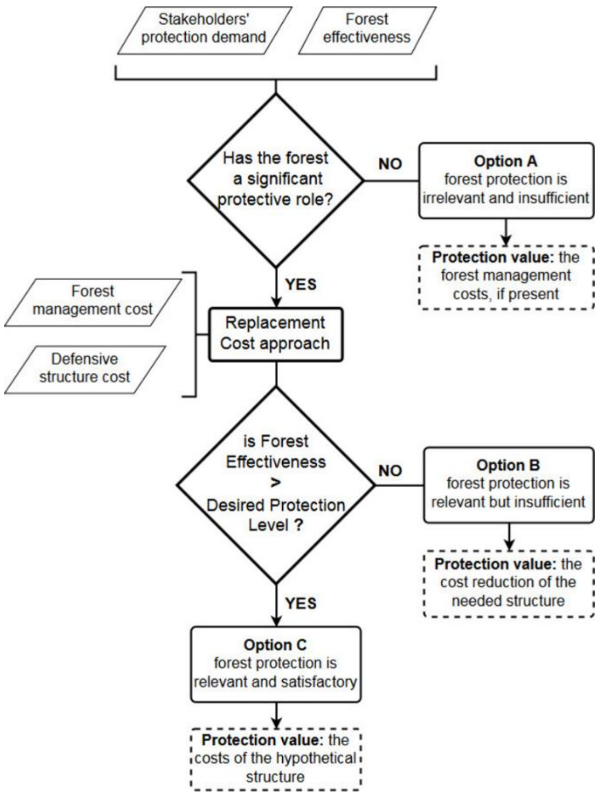

Figure 1: Conceptual framework of the ASFORESEE (Alpine Space FORest Ecosystem Services Economic Evaluation) model.

The present framework defines three possible options to evaluate the protective service, to be selected in consideration of the characteristics of the case study. Firstly, the role of the forest has to be verified in relation to the need for protection of the stakeholders (Section 2.2) and its effectiveness against rockfall events (Section 2.3). In case the latter results insufficient, Option A should be chosen. Alternatively, the Replacement Cost approach is adopted (Section 2.6), assessing the expenditures related to defensive structures (Section 2.4) and forest management (Section 2.5). Finally, a further discrimination is set to evaluate the forest performance in the light of a target protection level set by stakeholders. In the Option B, artificial protective measures (hereinafter "needed facilities") are necessary to enhance the protection service supplied by the stand, which alone is not sufficient to fulfil the target protection level. Conversely, for Option C the stand effectiveness is sufficient, and the costs of hypothetical artificial protective measures are assessed in order to quantify the forest protective value.

5.2.2 Demand for Protection

The protection ES against rockfall provided by the forest to society only occurs when there is a need for this protection (Grêt-Regamey, Brunner, and Kienast 2012). Therefore, in order to measure the value of this service, its demand should also be assessed (Villamagna, Angermeier, and Bennett 2013). For the regulation ES, the demand of this service can be defined via a qualitative evaluation, considering both technical (e.g. the economic value of the exposed asset) and social factors (e.g. its frequentation or relevance for the local community) (Villamagna, Angermeier, and Bennett 2013). Nonetheless, the level of protection expected by stakeholders, which defines a threshold of "acceptable risk", can range widely in relation to the importance of the goods at risk (Wolff, Schulp, and Verburg 2015). In some contexts, the effectiveness of a forest in protecting the exposed assets could result sufficient to fulfil stakeholders' expectations. However, in cases where the goods at risk are considered particularly valuable, the need to resist any possible event, regardless of its intensity and frequency, justifies the implementation of artificial protection measures able to provide the expected level of protection (Fidej et al. 2015). Therefore, a proper protection demand assessment is essential to understand whether the effectiveness of a forest is sufficient or needs to be integrated. In the ASFORESEE model, the demand for protection is currently assessed in a qualitative way, involving the stakeholders affected by the rockfall risk. The actors involved in the study constituted a focus group of representatives of the academia, local forest officials in charge of the planning and management of the forest, and consultants for the public safety of the area. Their contribution has been collected through a specific workshop set up to acquire their expectations regarding the protection of the goods at risk, in a 3-steps scale (low–medium–

high). The variables considered were (i) the frequentation of the area, (ii) its importance for the local community, (iii) the protection measures already implemented, and (iv) its perceived or actual economic value. Finally, as shown in Figure 1, their qualitative evaluation is compared to the effectiveness provided by the forest, determining the most suitable option to assess the value of the protection service.

5.2.3 Forest Effectiveness

The ability of the forest to mitigate rockfall events has been defined for ASFORESEE by adopting an index capable of measuring the effect of the trees in reducing the frequency and intensity of the phenomena. Therefore, we only took into account those rockfall events where the forest can provide an effective protective service, i.e. in the case of falling blocks with a volume not exceeding 10 m3. Firstly, the protection forest should be partitioned, if necessary, into stands with homogeneous structural features (Neuwenhuis 2000). The boundaries of these stands might have been already defined within the Forest Management Plan. If the protection forest is composed of different stands, the evaluation should be carried out separately for each homogeneous area and then weighted according to the size of each stand and summed into one single value.

Several methods assessing the stand effectiveness in rockfall protection can be found in literature. In this study, we adopted the Rockfall Protection Index (RPI), developed within the ARANGE project (Cordonnier et al. 2014) for its ability to provide the model of a synthetic measure of the effectiveness of the forest in stopping the falling blocks. In any case, it is worth underlining how these values remain independent from the model and are therefore adopted as mere input data. This index is based on a statistical approach for the computation of the maximum energy developed by the falling rock along the slope, consequently estimating the effectiveness of the forest to stop it. This service is measured with a value between 0 and 1 in relation to the percentage of falling boulders stopped by the protection forest situated along their trajectory. The input needed to compute this index, whose validity is constant within a homogeneous forest stand, are the following:

- Volume (m^3), mass (kg) and shape of a block having a diameter equal to the 95th percentile of those measured during the field data collection phase;
- Maximum cliff height (m);
- Linear distance (m) between the rockfall source and the forest stand;
- Slope (°);

- Main dendrometric parameters of the stand, such as density (n ha^{-1}), DBH (cm), and species composition (%).

Further information concerning the features of this index and its parameters can be found in the ARANGE project report (Cordonnier et al. 2014), where the RPI equation is extensively reported and described.

5.2.4 Defensive Facilities

In order to harmonize the structural characteristics of the needed or hypothetical defensive facilities (introduced in Section 2.1), capable of supplying the desired protection service, ASFORESEE adopted the most common typology of structure available: rockfall nets. These barriers are a passive defense structure constituted by a hexagonal mesh on metal poles fastened to the slope (Gottardi and Govoni 2010). The adoption of this structure is supported by several reasons, such as their widespread use in mountainous areas, their versatility, cost-effectiveness, and easy installation (Rimböck et al. 2014). Moreover, due to a specific European regulation defining building and testing methodologies, called ETAG027 (EOTA 2012), it is possible to standardize their sizing, enabling the adoption of a common design. Therefore, these guidelines have been employed by ASFORESEE in sizing the artificial defensive facilities in relation to the features of the rockfall phenomena. The main parameter needed for this operation is the target kinetic energy E_k, i.e. the energy developed by a falling block having a 95th percentile diameter. This parameter reflects a standard and precautionary approach commonly adopted in such evaluations (Notaro and Paletto 2012; Bianchi et al. 2018). Following a probabilistic approach, the value of the 95th percentile of the falling blocks is defined consequent to a field survey, where the fallen blocks, deposited in transects along a slope gradient, are measured by their diameter and density (Dussauge, Grasso, and Helmstetter 2003). We purposely adopted this parameter since it is consistent with the input data needed for the RPI, in order to facilitate the field surveys. The equation adopted to compute this value is derived from the ETAG027 and integrated with the ISO 11211-4: 2012 technical norm, which defines the safety factors in designing the nets, in accordance with the precautionary principle (Gottardi and Govoni 2010; Giacchetti and Grimod 2014). In consideration of these aspects, the E_k is computed, as shown in Equation (1):

$$E_k = \frac{1}{2} \cdot TB \cdot S^2 \cdot \gamma_R \cdot \gamma_B \cdot \gamma_T \quad (1)$$

where E_k is the target kinetic energy in kilojoule (kJ), that is the energy of the target block hitting the net; TB is the mass of the spherical target block, estimated as the product of rock density (in $kg \cdot m^{-3}$), the diameter of the 95th percentile of the falling rocks (cm), and π value (Bourrier, Lambert, and Baroth 2015); S is the testing speed of the rock, equal to 25 m s^{-1}, as stated in the ETAG027 regulation (EOTA 2012); γ_R is a risk factor assuming values between 1.00 and 1.20, following an increasing level of risk for people and goods, as established by ETAG027 regulation; γ_B is a block factor considering the reliability of the data adopted to estimate the mass of the target block, assuming values from 1.02 to 1.10 with decreasing data quality; and γ_T is a topographic factor that considers the uncertainties related to the topographic information available on the area at risk, assuming values from 1.02 to 1.10 with decreasing data quality.

The adoption of the 95th percentile as reference value for the E_kproves the precautionary approach laying behind the ASFORESEE, particularly for its influence on the defensive facility sizing. This approach is consistent with several other experiences on protection systems, such as (Faber and Stewart 2003; Bründl et al. 2009; Prina Howald, Abbruzzese, and Grisanti 2017), and inspired by the risk averse attitude of decision-makers responsible for the safety of dwellers and infrastructures. Additional precautionary measures are represented by the adoption of the Service Energy Level (SEL), an additional safety factor acting as a multiplier of the E_k with a constant value of 3, as stated in the ETAG027 regulation (EOTA 2012). The resulting value determines, via a matrix linking value ranges with corresponding parameters of the facility, the most relevant elements of the facility, i.e. height and resistance of the materials. Thus, the designed facility is compliant with current European regulations, capable of withstanding multiple impacts whilst suffering a minimal efficiency reduction and does not require any extraordinary maintenance activity (Giacchetti and Grimod 2014). Once the height and resistance of the facility have been defined, its sizing is completed by its width, equal to the extension of the slope subject to rockfall phenomena. Within the present model, one line of net barrier has been considered sufficient to replace the effectiveness provided by the protection forest. This assumption is consistent with the range of events in which forests can play a relevant role (L.K.A. Dorren and Berger 2006) and satisfies the requirements of least expenditure, given an equal level of effectiveness, established by the Replacement Cost approach (Bockstael et al. 2000).

The last step is the definition of the overall cost of the structure in a standardized way, supplying the overall sum that constitutes the basis of the Replacement Cost approach (Bianchi et al. 2018). To compute this value, several sources can be applied: among others, national or regional public works price lists; unitary building costs of similar structures, and values derived from scientific and grey literature (Faber and Stewart 2003; EOTA 2012; Piedmont Region 2018). The computation also includes indirect costs related to the implementation of the facility, e.g. administrative and supervising expenditure, direct costs were increased by 25%, in accordance with (Brun, Blanc, and Mosso 2012). Concerning maintenance costs, they were not computed due to their reduced influence on the performance of the barrier within such a limited service life [59]. Similarly, costs for replacing the facility at the end of its service life were not computed because not included within the timespan considered for this case study (25 years). Applying this procedure, the expenses needed to build an artificial defensive facility are estimated adopting a 2% interest rate. According to (Freeman III, Herriges, and Kling 2014), and as also showed in several similar studies (Bianchi et al. 2018), this value is the most suitable for discounting costs of public expenses having a lifetime similar to the one considered in this study and when the benefit and cost flow concerns only the present generation.

5.2.5 Forest Management

The final element that contributes to the protection value definition is represented by the silvicultural activities carried out in the stand. It is largely acknowledged how the capacity of unmanaged forests to stop falling blocks is naturally subject to fluctuations over time of their ability (L.K.A. Dorren and Berger 2006). Forest effectiveness can be hampered, among other factors, by dead trees, sub-optimal tree densities, or species composition, all factors that active management can improve (Motta and Haudemand 2000). Silvicultural activities in rockfall protection forests mainly consists of diversifying the stand structure, by means of interventions routinely performed every 10 to 15 years (Rammer et al. 2015), to support the establishment and development of a 40-cm-or-more diameter tree class and an abundant regeneration. This approach aims to maintain, and possibly increase, the level of protection provided by the forest stand, ensuring in the meanwhile, its resilience, stability, and perpetuation. From an economic perspective, these interventions often result in negative stumpage values, due to the high harvesting costs, the low productivity rates of the operations and the low quality of the achievable assortments, as they are frequently located on steep slopes (Bianchi et al. 2018; Accastello et al. 2018). ASFORESEE estimates the management expenditures, using the following input data:

- Area of the forest stand subject to the interventions (ha);
- Number of interventions scheduled in the same area (*n*);
- Growing stock (m^3 ha^{-1});
- Current annual increment of the stand (m^3 ha^{-1});
- Harvest intensity on the growing stock (%).

Since these data are usually included in the dendrometric information contained in the Forest Management Plan of the stand, their computation does not require any further data collection phase. Whereas the plan was missing, an additional effort is required to hypothesize, together with local forest managers, the features and costs of the forestry operations to be implemented in the stand. In this study, the Spatial-based Economic Model (SEM), developed by (Accastello, Brun, and Borgogno-Mondino 2017), was adopted to compute the intervention cost of the planned interventions. SEM enables the computation of the stumpage value of a forest harvest by comparing different working strategies and considering the environmental and logistic features of the stand and their influence on the productivity of the intervention. The net present value and the annuity value (Blanc et al. 2019) of the forest management expenses has been computed by totaling the discounted stumpage values of the planned interventions, based on the price of the assortments collected with a survey on the local timber market.

5.2.6 Replacement Cost Value

Once the components of the ASFORESEE model have been defined, the monetary evaluation was deployed using three alternative options. These options encompass all the possible conditions determined by the different relationships between forest effectiveness and the stakeholder needs. The description of these options is reported below:

Option A. The forest does not reduce the rockfall risk in a significant way, with the result that it is irrelevant for protection;

Option B. The forest significantly mitigates, but does not eliminate, the rockfall risk;

Option C. The forest is fully effective in mitigating the considered rockfall event and can be considered as a reliable Eco-DRR.

These alternative options represent the cornerstones of ASFORESEE, enabling the definition of the most suitable approach to evaluate the protection ES provided by the forest. Each of these options imply the use of a different equation, developed to provide a protective value capable of reflecting the real role of the stand in risk mitigation. Therefore, in consideration of both supply of and demand for protection, the evaluation is performed for each option as follows:

Option A. Here the protective role of the forest is marginal, as it is unable to significantly reduce the rockfall risk and, consequently, does not satisfy the need for safety of the stakeholders. Hence, in option A, the protective value of the forest is null, because of the inability of the forest to mitigate the risk and/or the lack of interest in the protection service by the stakeholders. Nonetheless, if an opportunity for the stand to develop relevant protective features within the ASFORESEE timespan is detected, the protective value of the forest can be estimated as the expenditures incurred to support this improvement with dedicated silvicultural interventions. This management decision is justified by the legitimate expectation that the benefits deriving from targeted interventions will enable the stand to acquire relevant protective features in the future. Therefore, Equation (2) measures the protective value against rockfall:

$$P_v = \sum_{i=0}^{t} M_i \cdot \frac{1}{(1+r)^i} \tag{2}$$

where P_v is the protection value of the forest against rockfall risk; M is the difference between the possible revenues and the expenditures from the forest management, incurred in the period comprised between the present (0 in the equation) and the moment *t*, which corresponds to the considered timespan of the model, discounted at the present time *i* adopting the interest rate *r*.

Option B. The second option is applied when the forest stand cannot guarantee a sufficient safety level to satisfy stakeholder needs. On the other hand, the forest has a relevant and measurable protective effect on rockfall risk that should be acknowledged. Therefore, in order to reflect the benefits that the stand provides, its value is assessed by measuring the difference between the value of a standard defensive facility and the value of a smaller facility providing a protection equal to the forest. The comparison between the necessary facility and the hypothetical one, in the case of the stand having no relevant protective role, is performed adopting the approach described in section 2.4. Therefore, the measurable reduction of E_k provided by the forest determines a defensive structure of smaller size and, consequently, lower expenditure. In option B, the replacement cost value is then estimated, as shown in Equation (3):

$$P_v = F_s - F_{wf} - \sum_{i=0}^{t} M_i \cdot \frac{1}{(1+r)^i} \tag{3}$$

where P_v is the protection value of the forest against rockfall risk; F_s would be the expenditures incurred to build a standard defensive facility, and replace it at the end of its service life, if no protective effect of the stand existed; F_{wf} are the expenditures to build a smaller necessary facility, which takes into account the benefits supplied by the forest; M is the difference between the possible revenues and the expenditures from the forest management, incurred in the period comprised between the present (0 in the equation) and the moment *t*, which corresponds to the considered timespan of the model, discounted at the present time *i* adopting the interest rate *r*.

Option C. The third option is adopted when the forest supplies such a high level of protection that the stakeholder need for safety is fully met, ensuring an effectiveness comparable with a defensive facility. Hence, the protection value will be equal to the expenditures of the hypothetical facility able to replace the stand, which provides the same performance (Bockstael et al. 2000). Nonetheless, the equation is integrated with a reduction coefficient applied to the protection value, in order to consider the real performance of the forest, which, even if satisfying the local demand for this ES, not necessarily ensures complete protection. Since this reduction coefficient represents the percentage of falling blocks stopped by the forest, the RPI value mentioned in Section 2.3 has been adopted. Its value has been modelled assuming the target kinetic energy of a falling block of a 95th percentile diameter, in accordance with the defensive facility sizing. This reduction coefficient has not been adopted in option B since, there, the comparison did not focus directly on the forest, but rather involved two structures differing in size: one considering the effects of the forest and one not. As in the previous options, management expenses are considered and subtracted from the overall amount (Equation (4)).

$$P_v = (F_s \cdot RPI) - \sum_{i=0}^{t} M_i \cdot \frac{1}{(1+r)^i} \quad (4)$$

Where P_v is the protection value of the forest against rockfall risk; F_s would be the expenditures incurred to build a standard defensive facility, and replace it at the end of its service life, if there was no forest; RPI is the reduction coefficient, between 0 and 1, to return the forest effectiveness to its actual value of effectiveness, equal to or lower than the designed defensive facility; M is the difference between the possible revenues and the expenditures from the forest management, incurred in the period comprised between the present (0 in the equation) and the moment t, which corresponds to the considered timespan of the model, discounted at the present time i adopting the interest rate r.

Once the protection forest is assigned to one of the available options and all the cost items involved in the model are computed, the protection value of the forest against rockfall events can be assessed. The monetary results of the evaluation can be alternatively expressed as a sum for the whole stand, as a sum per hectare or as an annuity value, obtained by discounting the overall value to the present time, standing the 2% interest rate previously adopted.

5.2.7 The Case Study

The ASFORESEE model has been tested on a study area in the Western Italian Alps in order to validate its results. The selected forest is situated in the Piedmont region of Italy, above the village of Beaume (45°04’36.1’’ N; 6°82’80,8’’ E; Figure 1).

Figure 2: The image represent the location of Piedmont Region and the village of Beaume (black location pin), where the case study is set.

This forest is actively managed since decades to preserve its protective service towards buildings and their inhabitants against the risk of rockfall from the cliff above it. The stand, owned by the Municipality itself, is an endalpic Scots Pine forest (*Pinus sylvestris* L.) of 10 ha, with large trunk diameters prevailing. The need for protection from rockfall risk, manifested by local sources (personal communication of the public forest managers) is high, since the rockfall activities are well-known, with potential partial damages to structures and goods, deriving from the falling blocks.

5.3 Results

The results of the application of ASFORESEE in the selected study area are reported below. For this study, the model operates within a 25-year timespan, which corresponds both to the service life of artificial facilities in standard conditions (EOTA 2012) and a reliable timespan for forest operation planning (Motta and Haudemand 2000). Concerning forest effectiveness, the characteristics of the stand and of the falling blocks were collected. Their values are shown in Table 1.

Table 1: Study area data constituting the ASFORESEE input to compute the Rockfall Protection Index (RPI).

Element	Information	Value	Unit of Measure
Forest stand	Mean DBH	29.4	cm
	Tree density	289	n·ha
	Stand area	10	ha
	Coniferous	89	%
	Broadleaves	11	%
Block	Diameter 95th percentile	0.65	m
	Rock density	2700	$kg \cdot m^{-3}$
	Cliff height	60	m
Slope	Height difference	120	m
	Mean slope	37	°
	Width	90	m

The second step consisted in the measurement of the kinetic energy generated, in accordance with Equation (1). The values of the components for the study area are listed in Table 2. For the definition of these risk factors, the information collected from the stakeholders while assessing the demand side of the ES resulted relevant. In particular, the γ_R factor assumed a value of 1.10, in consideration of the moderate residual risk for people and goods in the area. The remaining two safety factors, γ_B and γ_T, assumed the least possible value (1.02) due to the high-quality level of the data, respectively resulting from sampling the fallen blocks in the field and the high definition of the Digital Terrain Model (1 × 1m) adopted to compute the RPI.

Table 2: Factors used to compute the kinetic energy.

Kinetic Energy Components	Value	Unit of Measure
Mass of the project block $\boldsymbol{PB}$	6750	kg
Block speed $\boldsymbol{S}$	25	$m \cdot s^{-1}$
Risk factor $\boldsymbol{\gamma_R}$ (1–1.2)	1.10	-
Block mass factor $\boldsymbol{\gamma_B}$ (1.02–1.1)	1.02	-
Topographic factor $\boldsymbol{\gamma_T}$ (1.02–1.1)	1.02	-

The size parameters of the hypothetical facility to be built in absence of the forest were computed by employing the SEL coefficient. Therefore, the defensive facility should be 6 meters high and 90 meters wide. Finally, the forest management interventions were planned together with the local forest managers responsible for the stand and the information available in the FMP. The area to be harvested was measured and two interventions were planned. Detailed information concerning these harvests are reported in Table 3.

Table 3: Information concerning the harvesting operations planned in the forest.

Management Data	Value	Unit of Measure
Harvested area	7.27	ha
Number of interventions	2	n
Growing stock	293	$m^3 \cdot ha^{-1}$
Annual increment	1.33	$m^3 \cdot ha^{-1}$
Harvest intensity	20	%

Once all the information was collected, data describing the technical performances of the forest and the hypothetical facility were computed (Table 4).

Table 4. The technical results computed by ASFORESEE.

Technical Results	Value	Unit of Measure
Kinetic energy of the project block	2669	kJ
RPI	0.99	-
Kinetic energy absorbed by the forest	2519	kJ
Residual kinetic energy	150	kJ
Height of the hypothetical facility	6	m
Width of the hypothetical facility	90	m

In consideration of the aforementioned evaluation options, ASFORESEE assigned the study case to option C, where the forest satisfies the stakeholder need for protection. In this area, even though the demand for this protection ES of the forest is high, the forest proved to be effective in mitigating the risk, corresponding to only 150 kJ not absorbed by the forest. Therefore, to value the protection service supplied, Equation (4) has been applied. The cost of the hypothetical facility was computed referring to market values reported in the regional price lists of Piedmont. For the study area, the Piedmont Region 2018 price list for public works has been adopted (Piedmont Region 2018). Based on its values, the overall building costs of the facility resulted in 316,400€. Concerning the management of the area, the discounted expenses for the interventions were estimated in 8850€, as computed by the SEM (Table 5).

Table 5. The monetary results computed by ASFORESEE.

Economic Results	Value	Unit of Measure
Cost of the hypothetical facility	316,400	€
Forest management cost	8850	€
Value of the protection forest	304380	€
Unitary value	30440	$€\cdot ha^{-1}$
Annuity value	950	$€\cdot ha^{-1}\cdot year^{-1}$

Therefore, the overall protective value of the forest stand against rockfall risk is 304,380 €, corresponding to 30,440 € ha^{-1}. In order to provide more understandable information to stakeholders and decision makers, the results of ASFORESEE were expressed also as annuity value, i.e. the discounted yearly revenue generated by the forest for its protective role. For our case study, this value is equal to 950 €/ha/year, confirming the high value of the service supplied.

5.4 Discussion

The Replacement Cost method, which constitutes the basis of ASFORESEE, resulted to be suitable for the aims of the model and capable of estimating the value of a single ES of the forest such as protection against rockfall. When compared to other evaluation methods, this approach enabled the value to be directly derived from the market prices of the goods selected to hypothetically replace the forest, minimizing the subjectivity of the evaluation (Notaro and Paletto 2012). This aspect actually represents one of the most relevant results provided by ASFORESEE: the broad reliance on technical data and input from other models (such as the RPI), greatly reduces the assumptions of the users and ensures its wide replicability. Even if, in some cases, this aspect could represent a limitation to the application of this approach, as far as the ES considered is merely a mechanical interaction between trees and rocks, the comparison with a corresponding artificial facility is suitable and reliable (Bockstael et al. 2000).

Concerning the need to define the least costly substitute of the forest function (Bockstael et al. 2000), ASFORESEE satisfies this requisite by adopting the ETAG027 European guidelines, which allow the design of a standardized and cost-effective structure (EOTA 2012). Although kinetic energy may not always be a sufficient reference factor to design a facility, it has been proven how this value represents the most relevant factor (Grimod and Giacchetti 2014). Nevertheless, the precautionary approach adopted by ASFORESEE ensures a wide safety margin by including three safety factors in Equation (1) and considering the 95th percentile for the target block. Therefore, we can affirm that the subjective assumptions in the model are minimized both from the perspective of the needed protection level and of the design of the replacement facility.

Further intrinsic limitations of the model concern the substantial difference between defensive facilities and protection forests. Whereas the former can be designed in relation to the safety needs and the specific existing risk, the performances of the latter can be enhanced only partially via dedicated management solutions, often with negative drawbacks in the short term (Motta and Haudemand 2000). Moreover, the operations needed to improve their protective effectiveness often leads to negative stumpage values (Accastello et al. 2018), as occurred in our case study. Nonetheless, ASFORESEE does not only consider profitable forest interventions, rather, it computes the stumpage value of all interventions that should be performed in order to maintain or increase the effectiveness of the forest stand. Conscious of the difficulties of performing such interventions, especially in areas interested by abandonment and poor implementation of the planned forest operation (Accastello et al. 2018), we nonetheless aim to highlight their potential returns in terms of safety and risk mitigation, as attested by the high protective value of the stand. Finally, the temporal frame considered by the model represents a relevant variable that may influence its results. The protective function of a defensive facility effectively remains constant in standard environmental conditions during its service life, and then collapses abruptly at its conclusion (Faber and Stewart 2003). Conversely, the forest stand is characterized by much longer dynamics, and is subject to unpredictable biotic and abiotic disturbances that can temporarily or permanently influence the ES provided (Bebi et al. 2017). For these reasons, we aim to test the model on different timespans in the future, in order to study the variations in value caused by both the benefits of a dedicated forest management and the increased costs of repeatedly substituting the defensive facility at the end of its service life, which are currently excluded from the evaluation. In a similar manner, the influence on the protective value of the forest resulting from the adoption of different interest rates will also be tested.

Although a real comparison with other studies results difficult due to the variety of methods and units of measures described above, the value obtained by testing ASFORESEE on a real case study are aligned to other similar experiences in the Alps where the Replacement Cost methods was adopted (Bianchi et al. 2018; Notaro and Paletto 2012). These studies, focusing on rockfall or avalanche protection, found comparable monetary values, comprised between 250 and 1900 € ha^{-1} $year^{-1}$, in relation to the effectiveness of the stand. On the other hand, studies with a different methodological background, focusing on the damages avoided by the forests, found annuity values close to 100,000€, due to the high value of the exposed assets (Bianchi et al. 2018). Concerning the defensive facility adopted to replace the forest, we can assume that the design of a real structure would imply further adaptations to local conditions, leading to an increase of the design and building costs. Therefore, we would consider the 950 € ha^{-1} $year^{-1}$ value of the protection service we estimated as a lower boundary. Nonetheless, when compared to other previous evaluations performed in similar contexts, we can reasonably assume that ASFORESEE generates valid results and thus provides the possibility to apply it to other contexts with minimal variations. The strengths of ASFORESEE can mainly be attributed to the high standardization of the defensive facility design process and diversified approach in computing the protection value using three alternative options. To all effects, the definition of different evaluation options reflects the specific conditions a protection forest may encounter and represents the principal innovative element of ASFORESEE.

Obviously, further actions are necessary to put the evaluations generated by ASFORESEE into practice. Among others, the definition of the demand side of this ES could be implemented with a deeper involvement of the stakeholders in the phases of facility design. Similarly, further research could enable the model to evaluate several gravitational hazards instead of focusing only on rockfall, since a similar methodological approach seems suitable for all gravitational hazards. Further analysis of the elements affecting the most the model outputs could also be implemented, e.g. applying a sensitivity analysis of the input factors of the model and a MonteCarlo simulation to study their combined influence on the results. Moreover, the relevance of such valuation is deployed only including Eco-DRR as protection forests, into the local risk management strategies (e.g. at municipality or catchment level) aimed at mitigating this natural risk in the most cost-effective way (Onuma and Tsuge 2018; Accastello, Blanc, and Brun 2019). In this respect, it should be noted how the protection value we measured is not an exchange value, but rather, the translation in economic terms of the benefits achievable through a dedicated management of the ecosystem generating it (Laurans et al. 2013). Nonetheless, as explained previously, similar valuations can represent a stepping-stone for the recognition of the ES value provided by the forest, and foster the implementation of dedicated management operations. In this regard, in order to improve the understanding of its measurement and widen its applicability, ASFORESEE expresses the result of the monetary evaluation in several ways. Therefore, the protective ES can be presented as a total value, in € per stand or in € ha^{-1}, or as a yearly benefit, in € ha^{-1} $year^{-1}$. Even if the latter form of valuation could lead to some misunderstanding, its adoption is widespread (Bianchi et al. 2018) and results to be the most suitable way to communicate with stakeholders, decision makers and other non-scientific actors given its immediacy and comprehensibility.

5.5 Conclusions

The risk mitigation against natural hazards, such as rockfall, is only one of the several ES that society benefits from mountain forests (Grêt-Regamey, Brunner, and Kienast 2012), whose multi-functionality should be enhanced by targeted management, as stated in several national and international regulations (EC 2013). In this context, our ASFORESEE evaluation model can support in recognizing the role of protection forests as a reliable, cost-effective and forward-looking Eco-DRR and enhance its consideration both among scientists and non-academic stakeholders. Similarly, the monetary evaluation confirms that the active management of protection forests can represent a sound investment to be integrated in local risk management strategies, in order to mitigate rockfall risks and ensure the livability of mountainous areas.

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Authors Contribution

Cristian Accastello was involved in the conceptualization, methodology development and writing (original draft preparation) of the study; Ettore Bianchi was involved in the conceptualization and methodology development; Simone Blanc was involved in the methodology development and validation of the study; Filippo Brun was involved in the writing (review and editing) and supervision of the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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6 Discussion and Final Conclusions

6.1 Overview on the studies

The concept of ES has been interested by a rapid diffusion in the scientific literature since its recent introduction, given its versatile adaptation and the possibility to precisely measure its features in space and time (Costanza et al. 2017; Bouwma et al. 2018). In the context of forest ES, several examples have already been published concerning the use of the ES concept for spatial analysis and support to land use planning decisions (Eastwood et al. 2016; Sacchelli and Bernetti 2019). In this light, the use of monetary valuation to translate different dimensions of the ES can assume a relevant role for the end-users of such assessments, given the possibility to communicate more easily understood its results, in comparison to other assessment methods (Häyhä et al. 2015; Masiero et al. 2019).

The fours studies presented above represent some examples of monetary valuation of forest ES within the context of the Italian Western Alps. Particularly, starting from the SEM tool presented in Chapter 2, the economic models have been interested by a stepwise development which brought to a continuous increase of their complexity. These improvements were also reflected in the relevance of the results, which evolved from relatively simple harvesting estimations to well-rounded environmental valuations of different forest ES. While first two applications of the model (see chapters 2 and 3) are more timber-oriented and aimed at optimizing the harvesting operations in the difficult conditions that characterize the Italian Alps, the following implementations proved its versatility in fitting the different conditions and objectives that can occur in the mountainous environment. In fact in Chapters 4 and 5, focusing more on land use and land use change-related issues, the model outputs provided relevant information not only to local forest managers, but also to decision-makers with general interests in natural hazard mitigation and land use planning in order to enhance the value of local natural resources.

From the methodological perspective, it is worth noting how the results of the studies have been validated from both a statistical analysis and several discussion rounds with local stakeholders and experts. Chapter 3, among others, deepened the theme of the statistical analysis of both the model and its output, proposing a methodology suitable for being replicated also for the following applications. The replication of this sensitivity approach will provide the users of additional information regarding the parameters influencing the most the outputs of the valuations, allowing for a more cost-effective data collection phase.

Concerning the methods selection, as already briefly pointed out in the previous chapters, the tools developed in the thesis mostly lie on cost-based methods, as the replacement cost approach, or on market values for commodities as timber and carbon credits (Masiero et al. 2019). While these methods resulted to be the most suitable for the aims of the valuations, it is worth considering the possibility to widen the number of valuation approaches adopted when adding more forest ES to those already analysed. Particularly, several examples already exist of studies adopting preference-based methods to value the cultural ES of a forest stand, or for regulation ES with a clear demand side (Olschewski et al. 2012; Paletto et al. 2013; Fish, Church, and Winter 2016). The inclusion of such methods would clearly enhance the possibilities to adopt the different economic model here developed also in other contexts. Nonetheless, any future application would need a careful selection of the most suitable method, taking in consideration the features of the case study, the objectives of the valuation, the stakeholders possibly involved and the final recipients. Only the adoption of a method able to provide results in a suitable and easily understandable way, which can vary in relation to the knowledge of the recipients, will allow the achievement of the initial aims of the study.

Another aspect affecting the relevance of the results concerns the replicability of the models. Notwithstanding the territorial homogeneity of the different case studies presented in the chapters of this thesis, we believe the relevance of their outputs should be regarded as sufficiently representative to ensure the validity of the results. In fact, different forest typologies (both broadleaves and conifers) have been considered, and several harvesting methodologies run by different companies (logging or agricultural entrepreneurs) have been investigated in order to provide a balanced picture of the versatility of these models. Additionally, the forest stands of Piedmont can be considered representatives of Alpine forests in general, due the harsh growing conditions of the trees, the limited road network, the altitude where the stands are located and the complex socio-economic patterns that have interested their management in the past century (IPLA, 2007). For these reasons, the methodologies and the outcomes of the valuations can be considered valid and replicable also in other mountainous context, especially in Europe, where examples of other marginal areas interested by land abandonment, property fragmentation and discrepancies between ES demand and provision are frequent (Garcia-Hernandez et al. 2017;Beato Bergua, Poblete Piedrabuena, and Marino Alfonso 2019). Their adoption in new contexts could go hand in hand with a further deployment of the models, e.g. improving the input data base of the SEM or widening the ASFORESEE model to all gravitational hazards.

To conclude, within the context of ES monetary valuations, the abovementioned economic models present several aspects of innovativeness. First of all, to our knowledge, they represent the first example of economic models specifically designed to work in mountainous environments, therefore taking into account all the peculiarities these areas entails. Among these, we have: i) the reduced productivity of the forest stand, which influences the timber production; ii) the topographic and logistic limitations due to the local orography, and iii) the inherent provision of bundles of ES, whose management requires to highly consider the manifold trade-offs and lag times that can originate. Then, also the detail level of these models is peculiar in respect to similar experiences available in the scientific literature. The SEM and its following applications in fact clearly focus on a stand-oriented perspective, which delivers detailed results valid at local level. This feature also influence the third main quality of these studies, which is the ability to enlarge the information basis of decision makers and forest managers, steering their decision processes in order to take in account the different ES variations in demand and supply that will originate. In this light, the economic methods applied in the studies showed to fit the requirements of the valuations and provide valuable results, giving value to the high level of detail of the input data. On the other, their limitations in being applied at larger scale, which have been largely discussed in the available scientific literature (Masiero et al. 2019), suggest a discussion on whether they should be adopted or not in case studies with larger spatial scales. Finally, for what concerns the temporal scale of the valuations, the most relevant issues mainly concern the quality of the input data rather than to the methods adopted. In fact, the difficulties in foreseeing socio-economic, land use and climate change-related variations in the future represent an impediment to perform reliable valuations in the long-term, especially with the level of detail delivered by the models described above (Houet et al. 2017; Thaler et al. 2019).

6.2 Results and future challenges

It is in the intentions of the author to proceed in the development of the models presented above and enhance their performance in order to support the local decision-makers on risk and land-use related issues. In this regard, it is worth highlighting how the outputs of this thesis have already been involved in a follow-up project that will enable the overcoming of the limitations described above. Particularly, the Interreg Alpine Space project “GreenRisk4Alps”, started in April 2018, focuses on delivering multi-risk management strategies to local decision makers. These strategies are achieved in different subsequent steps, i.e.: hazard mapping, risk modelling, vulnerability assessment and comparison of different risk mitigation strategies based on their cost-effectiveness. This project will support the enhancement of the objectives already achieved during the “ROCKtheALPS” Interreg Alpine Space project, enlarging the focus to several natural hazards and ensuring an early involvement of local stakeholders into the project, in order to deliver valuable output. In this context, the SEM model and its following developments will contribute in assessing the different costs and benefits ensured by the available protection measures, shedding light on the potential, often still unexpressed, protective effect of mountain forests, which has been effectively demonstrated in the Chapter 5 of the present thesis.

This project therefore represent a valuable opportunity to overcome the limits that affected the previous studies and provide local risk managers of an innovative Decision Support System (DSS) for the comparison of different risk mitigation measures, alone or in combination. The aim of this DSS is the identification of the most suitable solution for mitigating the risks of avalanche, debris slides and rockfall on selected profiles taking into account the need for protection expected by the stakeholders, the cost and benefits which every solution entails and their related social acceptability. Additionally, given the potentialities of the economic models here developed, this DSS will put a focus on the protective effects of Eco-DRR, as protection forest. Particularly, due to the variable time scale it can consider, the potentialities of these measures in combination with grey infrastructure will be investigated, highlighting the substitution effect they can ensure in the long term (Onuma and Tsuge, 2018).

Finally, also the possibility to adopt different economic methods will be tested during this project. In particular, in order to enlarge the territorial focus of the analysis and assess the willingness of the local stakeholders to pay for the provision of forest ES, an application of the discrete choice method is planned. This study, currently in preparation, will represent one of the first examples of such valuations applied for regulation ES, investigating the risk perception of tourist and local dwellers in regard of natural hazards and the different behaviours they can assume in relation to different combinations of mitigation measures. This study will therefore open a new perspective on the consideration of Eco-DRR in mountainous environments among local stakeholders and its implementation, aiming at supporting local decision makers with additional information to spread the adoption as Eco-DRR in their areas of interest. In relation to the case study features, the potential benefits that can be achieved through the application of these alternative methodologies are manifold. The economic valuation of forest ES can in fact contribute to highlight the value of the forest and its functions: previous works already showed how this kind of analysis can help the stakeholders to recognize the value of natural resources and raise the awareness on their sustainable use and conservation (Paletto et al. 2013; Schirpke et al. 2019). Moreover, when such valuations are focusing on local scale and require high detail levels, as it is in our cases, their potential role can deliver far beyond the simple awareness, going from accounting purposes to be fundamental components of priority-setting plans and to design instruments based on ES performances (Gómez-Baggethun and Barton 2013; Masiero et al. 2019).

In this light, the methodologies here adopted seem relevant to mainstream the adoption of ecosystem-based solution to fight the effect of climate change and natural hazards (Vandermeulen et al. 2011; Emerton 2017), two aspects which also constitute a core theme of the GreenRisk4Alps project mentioned above. In fact, part of its objectives are dedicated to test the influence of socio-economic variables and climate-change scenarios on the tool delivered to the risk managers. These measures, also known under the acronyms of EbA (Ecosystem-based Adaptation) and Eco-DRR are receiving an increasing support from governmental and scientific bodies for their features of "no-regret" measure and the manifold dividend their implementation can provide (Doswald and Estrella 2015; Nyman 2015; Renaud et al. 2016). Particularly, studies concerning the potential role of forests as EbA and/or Eco-DRR currently represent a gap in the scientific research, where most of the studies focus more on the modelling of the forest stand effectiveness, rather than on its integration with grey infrastructures and the benefits they inclusion can provide. In this light, introducing Cost-Benefit Analysis based on the SEM and the other models developed in the present thesis seems to be a promising focus area for the future developments of this work. As already highlighted in the studies from Accastello et al. (2019) and Onuma and Tsuge (2018), green measures have the potential to integrate avoidance and grey solution in specific contexts and against a variety of natural hazards, satisfying the level of protection needed by the stakeholders (Wolff, Schulp, and Verburg 2015) and providing new solutions to enhance the liveability of mountainous areas.

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