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A Spatial-Based Decision Support System for wood harvesting management in mountain areas

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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.

1. Introduction

Evaluating the exploitation costs of a forest harvest is a basic step in the stumpage price[1] 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).

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[1] Stumpage is a partial balance defined as: $S = p\,x - c(x)$, where:
p is the "price" of timber, that is, its market value per unit of timber assortment;
x is the quantity of timber, and
$c(x)$ is the cost of felling a unit of timber and transporting it to the market.

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[2] (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-

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[2] The total economic value (TEV) of a resource is the sum of its direct, indirect, option and existence values.

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. ***Materials and methods***

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.

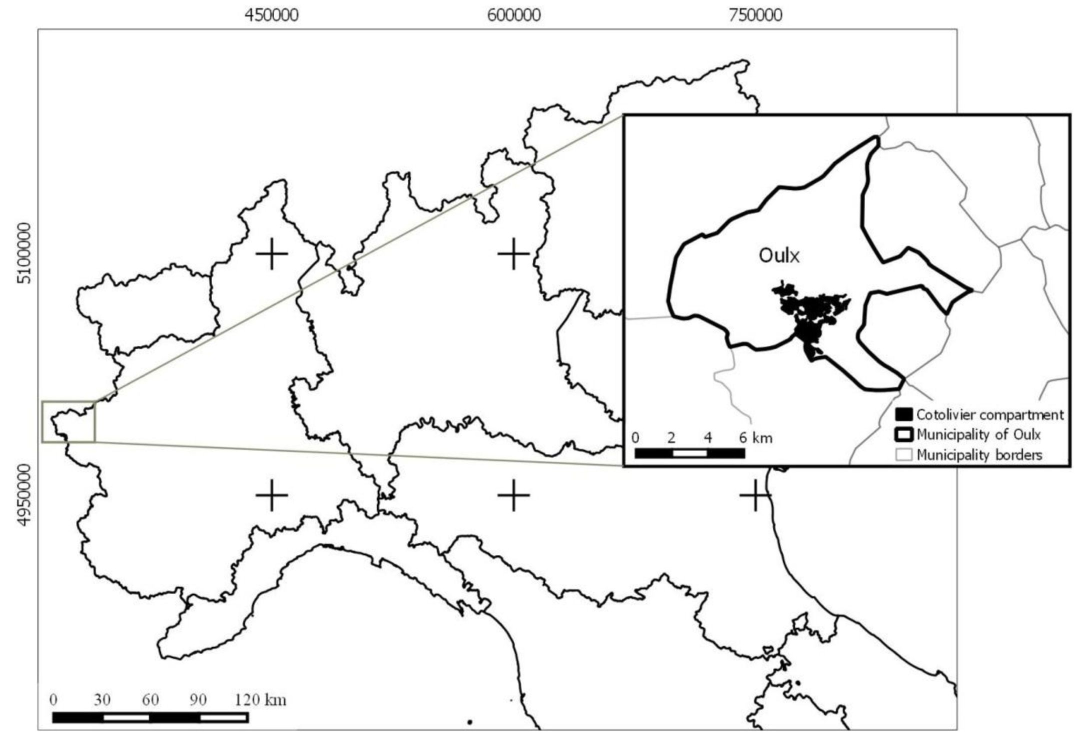

***Fig. 1** - Location of the study area in North-West Italy; the reference system is: WGS84 UTM 32N*

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. 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).

2.3. 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.

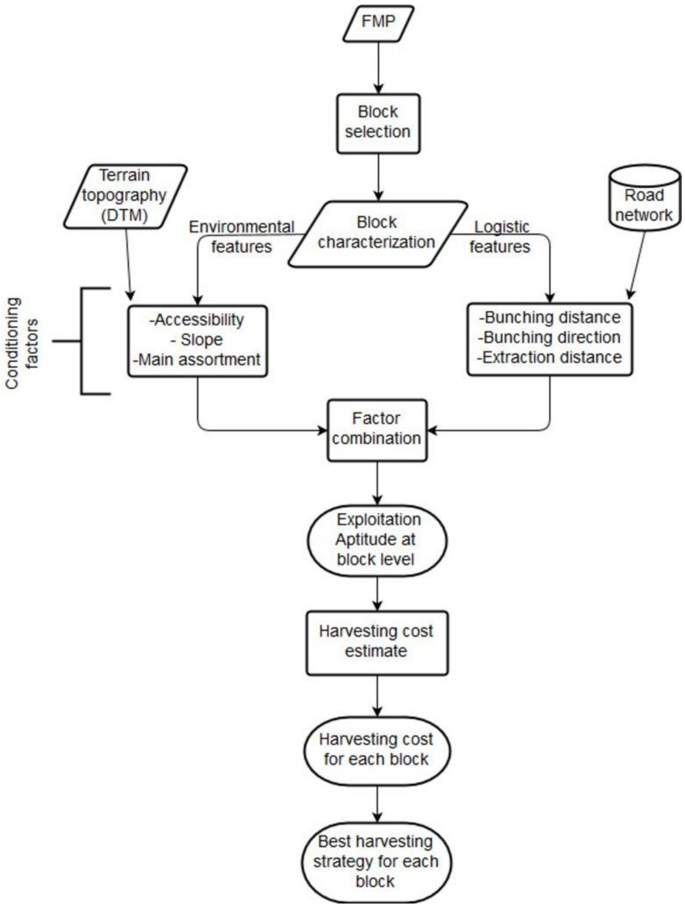

Fig.2 – Flow chart of the SEM framework

2.3.1 *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.

2.3.2 *Harvesting 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) e*xtraction (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
$S(x,y)$	*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
$B_d(x,y)$	*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).

2.3.3 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 ($A_g(x,y)$, $A_s(x,y)$, $S(x,y)$) and those depending on the harvest strategy ($B_d(x,y)$, $B_r(x,y)$, $E_d(x,y)$) 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)*).

$$\boldsymbol{BEA}(x,y) = [\mathrm{A_g}(x,y) + A_\mathrm{s}(x,y)) + \mathrm{S}(x,y)] \cdot [\mathrm{B_d}(x,y) + \mathrm{B_r}(x,y) + \mathrm{E_d}(x,y)] \qquad [1]$$

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.

2.3.4 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.

3 Results and discussion

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.

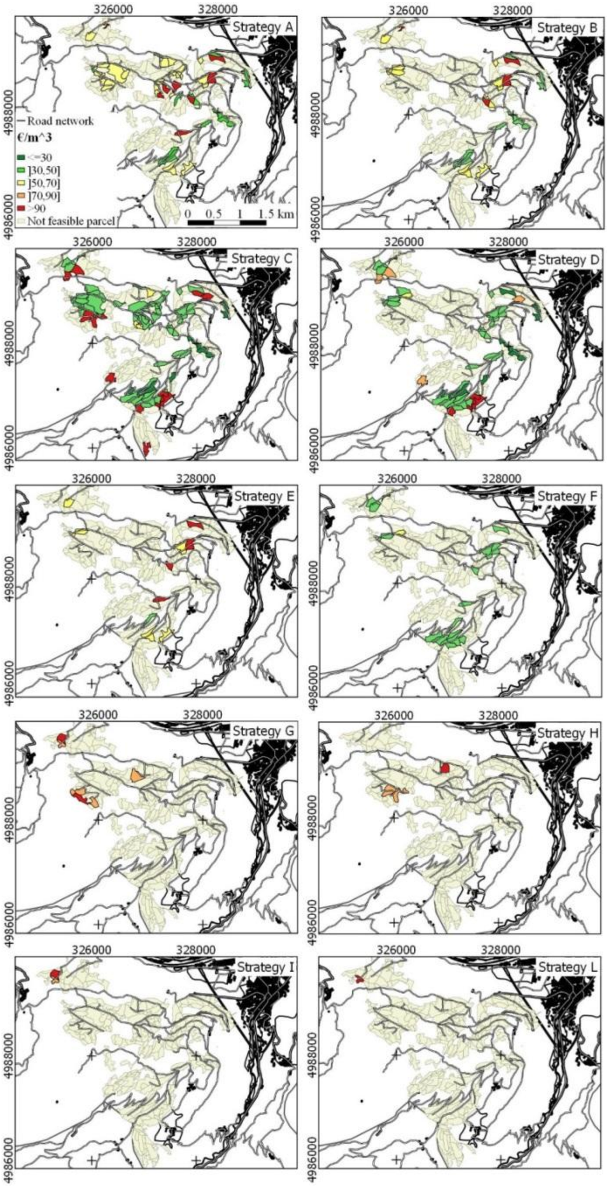

Fig.3 *– Maps of the cost-scenarios for the considered strategies. The reference system is: WGS84 UTM 32N.*

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.

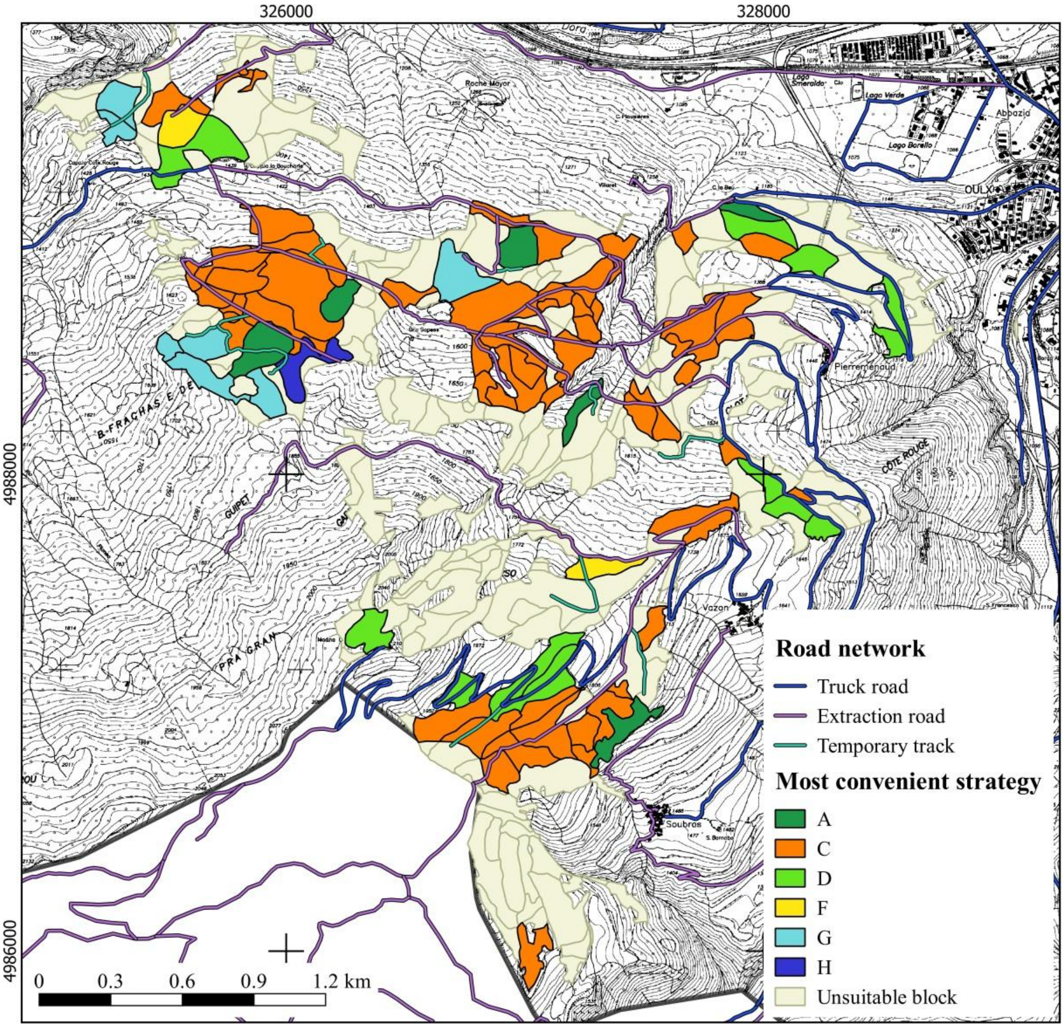

Figure 4 *– Map of the most convenient strategy for each block; the reference system is: WGS84 UTM 32N.*

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.

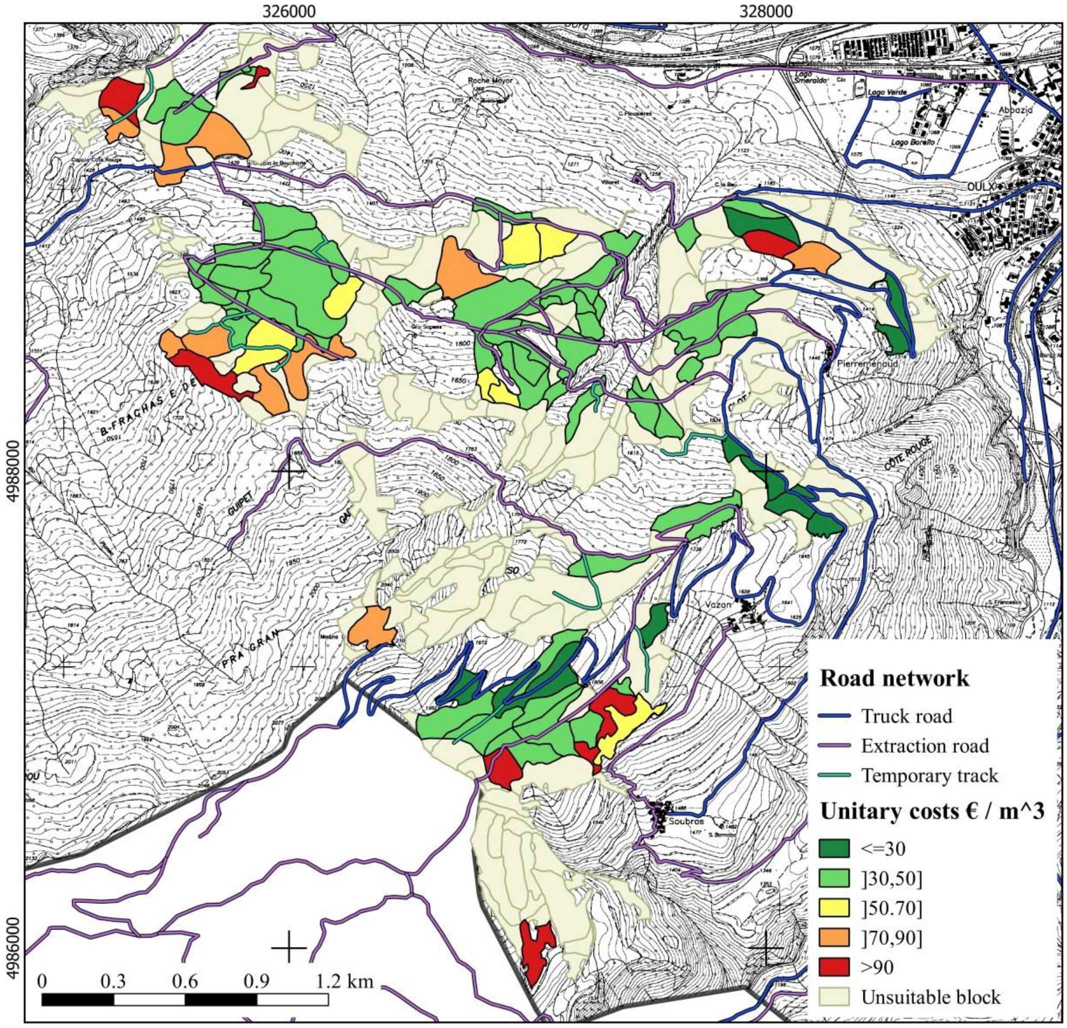

Figure 5 *– Map of the unitary harvesting cost of each block when the most convenient strategy is applied; the reference system is: WGS84 UTM 32N.*

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	**[n]**	***BEA***				**Unitary cost**			
		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.

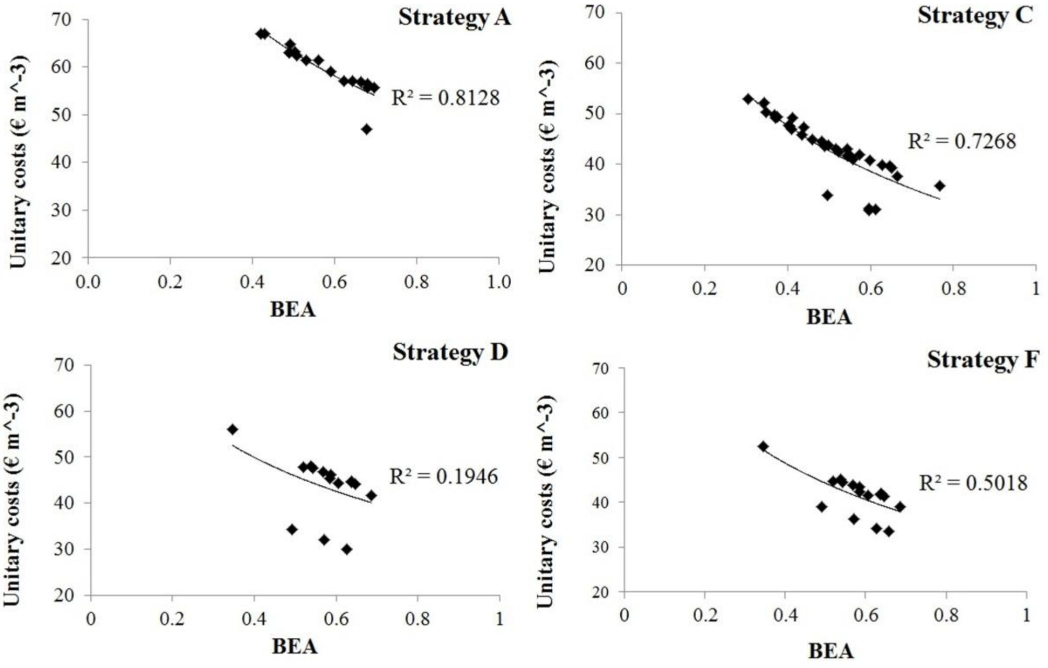

Fig. 6 *– Relationship between the unitary costs and BEA for the 4 most frequent strategies (A, C, D and F).*

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.

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[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.

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:

- 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.

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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