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

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1 A Spatial-Based Decision Support System for wood harvesting management
2 in mountain areas
3
4

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9
10 **Keywords**

11 Spatial modelling; mountain forest management, stumpage cost, economic valuation; DSS.
12

13 **Abstract**

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

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

34

35 **Highlights**

- 36 - Spatial-based economic model for the estimation of harvest costs of blocks;
- 37 - The model considers the morphological and operating features of the area;
- 38 - Economic estimates are defined according to the harvesting suitability of blocks;
- 39 - The approach constitutes a Decision Support System for forest managers.

40

41 **1. Introduction**

42 Evaluating the exploitation costs of a forest harvest is a basic step in the stumpage price¹ estimation, and
43 requires several skills in different work fields, such as economy, silviculture and exploitation planning
44 (Carbone and Ribaud, 2005, Picchio et al., 2011). Stumpage price evaluation is generally considered to
45 be the most appropriate methodology to evaluate mature or close-to-mature stands (López Torres et al.,
46 2016). It has been used frequently at both international (Chang, 1983, Sessions and Sessions, 1992, Mei
47 et al., 2010) and national level (Serpieri, 1917, Patrone, 1947, Borghese and Venzi, 1990), and it is
48 usually adopted in forest evaluations (Carbone and Ribaud, 2005, Carbone, 2009).

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.

49 Although several works have focused on particular aspects of this estimation, such as the definition of
50 all its components (Brun et al., 2009, Carbone, 2009) or its relationship to the purchase cost of public
51 auctions (Brannman et al., 1987, Pettenella, 1998), only a few have attempted to relate the economic
52 aspects to the spatial features. Few works have evaluated the Total Economic Value² (Pearce, 1990,
53 Plottu and Plottu, 2007) of a territory considering both its productive functions and ecosystem services
54 provided, at either local (Giau, 1998, Häyhä et al., 2015) or regional level (Grêt-Regamey et al., 2008,
55 Bernetti et al., 2013, Felardo and Lippitt, 2016). Other works, such as those by Adams et al. (2003) and
56 Huth et al. (2005) have proposed spatial-based models that were focused on harvesting risks and
57 impacts; on selecting the most suitable harvesting method (Yoshioka and Sakai, 2005, Kühmaier and
58 Stampfer, 2010), on addressing forest management and policies over large areas (Linehan and Corcoran,
59 1994, Puttock, 1995); or on evaluating timber availability and its harvesting costs at a regional level
60 (Nakahata et al., 2014). However, none of these works has dealt with the estimation of the harvesting
61 cost of logging operations at a stand level. A similar spatially explicit approach, aiming at optimizing
62 forest management from an economic point of view, was already presented in Härtl et al. (2013). There,
63 the stumpage price of harvests was computed in relation to the achievable timber volume, without
64 taking in account alternative strategies of work organization and environmental aspects of stands.
65 Similarly, the Biomassfor model (Sacchelli et al., 2013b) stands for its ability to match ecological and
66 technical data, assessing the economic results of harvest with the stumpage price method. On the other
67 hand, harvests are analysed at regional level, not identifying each considered stand.
68 The present work, which is based on the classical assessment method, presents a cost analysis for each
69 logging phase of a forest cut, and achieves an economic evaluation of an area managed by a local forest
70 consortium. In order to make the economic evaluations consistent for management purposes, a GIS-

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

71 based Decision Support System (DSS) was set up. DSSs are becoming common tools in the
72 environmental planning context, as they are able to integrate spatial information, economic evaluations
73 and operational issues (Thompson and Weetman, 1995, Segura et al., 2014) to optimise managers'
74 choices (Diaz-Balteiro and Romero, 2008). Many works concerning land use and land management
75 (Geneletti, 2004, Borgogno-Mondino et al., 2015a, Romano et al., 2015) reported the effectiveness of
76 these systems, and the positive consequences from their adoption have been pointed out (De Meyer et
77 al., 2013). Their application can be very versatile depending on the aim and territorial level. For
78 example, Sacchelli et al. (2013b) and Puttock (1995) related harvest costs to forest biomass while
79 Pussinen et al. (2001) and Nakahata et al. (2014) analysed cost dependently from spatial scale (national
80 to local). Moreover, to avoid subjectivity effects that can occur when non-homogeneous parameters are
81 simultaneously evaluated (Bottero et al., 2013, Sánchez-Lozano and Bernal-Conesa, 2017), DSSs are
82 often supported by Multi-Criteria Decision Making approaches, which allow factors pertaining to both
83 the territory and the environment to be considered simultaneously.

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

94 effective tool to support local forest managers' decisions (West et al., 2013), and would lead to several
95 benefits concerning planning and management activities (Angehrn and Jelassi, 1994, Hung et al., 2007).

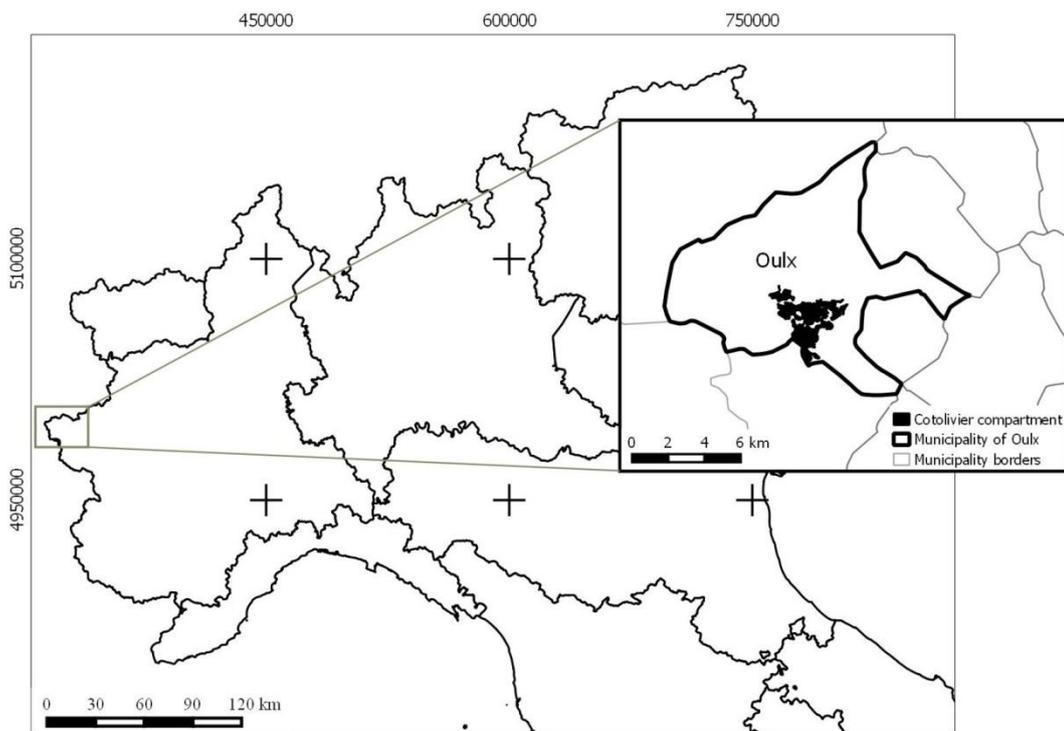
96

97 **2. Materials and methods**

98 **2.1. Study area**

99 The study area where *SEM* was built is located in the upper Susa valley, in the Piedmont Region, North-
100 West Italy. The compartment, part of the town of Oulx (Fig. 1), extends over 455.62 ha, and it is
101 included in the local Forest Management Plan (FMP), which is the current forest planning instrument.
102 This area has a widespread road network (average density of 55 m ha⁻¹); its altitude ranges from 1200 to
103 2100 m a.s.l. and the main forest category is represented by larch stands (*Larix decidua* Mill.), even
104 though Norway Spruce (*Picea abies* (L.) H. Karst.) and Scots Pine (*Pinus sylvestris* L.) stands can be
105 found at lower, north-facing sites. Larch reforestation is at present underway on the south-facing slopes.

106



107

108

109

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

110

111 This compartment was selected as a case study because of the productive destination of its forests, its
112 favourable orographic and fertility conditions and a long-standing active management. The latter
113 condition is due to the Consorzio Forestale Alta Valle Susa, a forest management consortium that
114 operates in the whole Upper Susa Valley. Its presence in the area has to be considered positively, since
115 in the Italian Alps, in spite of the steady spread of woods of the last decades (Gasparini and Tabacchi,
116 2011), the forestry sector supplies only 1% of the national primary sector income (Secco et al., 2017),
117 with a wood increment exploitation of 24% (<http://eurostat.ec.europa.eu>). This is one of the lowest rates
118 in Europe, even though the data should not be considered completely reliable because of illegal selling
119 on the local firewood market (Pettenella, 2009). This general situation is leading to an increasing
120 number of abandoned forests and under-exploited timber resources (Bätzing et al., 1996, Coppini and
121 Hermanin, 2007), negative aspects that can be faced through an effective management and a steady
122 timber market, two conditions ensured by the consortium.

123

124 2.2. Data

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

127 The *Map of the Stand Structure*, which is included in the FMP and supplied in polygon vector format,
128 depicts the vertical and horizontal organization of forest stands, according to their past management and
129 stage of development (IPLA, 2003); it also divides them into blocks (Armitage, 1998). These blocks
130 share a common stand structure, and represent the smallest management unit located by the FMP

131 (Bagnaresi et al., 1986). Because of their dimensions and homogeneity, the blocks were assumed as the
132 harvesting units on which silvicultural cuts are scheduled. The topographic features of the area were
133 mapped using the Regione Piemonte Digital Terrain Model (DTM), supplied in raster format with a 5-
134 meter grid size and a height tolerance=1.44 m (<http://www.geoportale.piemonte.it>). Qualitative data
135 related to the assortments, orography, road network and timber volume of the forest blocks were
136 obtained from the current FMP. Since the data were supplied as a text document (report), the relevant
137 information was selected and organised in a relational database. Other inputs were obtained from: a)
138 literature, regarding for example, technical and economic data on the organization of the logging
139 operations, productivity and hourly costs for machines and manpower (Hippoliti and Piegai, 2000,
140 Lubello, 2008, Blanc, 2010), and b) interviews with forest managers and workers, to define the features
141 and limits of the considered harvesting techniques.

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

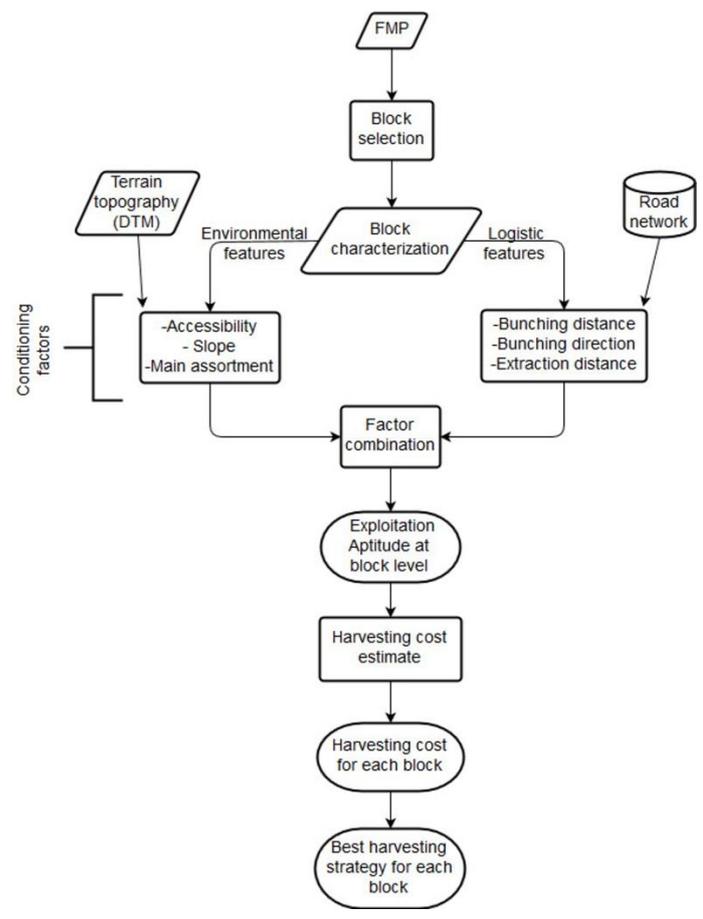
147 Several logging strategies were included in this model to identify the most suitable harvesting method.
148 With the support of the aforementioned forest consortium, it was possible to define accurately all the
149 fundamental technical and economic parameters in consideration of the forest and area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

152

153 *2.3. Spatial-based Economic Model*

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

158



159
160

161

Fig.2 – Flow chart of the SEM framework

162

2.3.1 Forest block selection

164 Since SEM aims at evaluating the financial efficiency of harvesting in productive forest stands, the
 165 suitable area was defined through a block selection. First, those blocks with a non-productive

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

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

183

184 2.3.2 *Harvesting strategies and limitations*

185 The standard harvesting operations in mountainous areas are organized in three stages: a) *felling and*
186 *processing (FP)* b) *bunching (B)* and c) *extraction (E)* (Akay, 2005, Nakahata et al., 2014). *FP* is
187 performed by cutting the tree, delimiting its branches, topping the trunk and bucking it to the
188 merchantable assortment; *B* consists of collecting the trunks and transporting them to the landing site on

189 an extraction track; during *E*, logs are hauled to a truck road. While *FP* can be achieved in a single step,
 190 other stages can be performed with different techniques, depending on the working organization and
 191 territorial features.

192 Ten *standard harvesting strategies* were selected for this study and coupled with the required
 193 machinery, namely, tractors, tracked tractors or skidders (Spinelli et al., 2006, Montorselli et al., 2010).

194 The different machineries are listed in table 1; the *FP* operations were performed in the same way for all
 195 of the different strategies.

196

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

200

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)

201

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

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

217
 218 **Tab. 2** –Description of the factors that condition the harvesting operations
 219

Raster Map Name	Information type	Description	Parent map	Factor values
$A_g(x,y)$	<i>topological</i>	Block accessibility related to rocks in relation to tractors	FMP	0.33 = high 0.66 = medium 1 = low
$A_s(x,y)$	<i>qualitative</i>	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
$S(x,y)$	<i>topographic</i>	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
$B_d(x,y)$	<i>topological</i>	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

$B_r(x,y)$	<i>topological</i>	Bunching direction, upward or downward to the nearest track or road	DTM	Downward for manual logging U_w or D_w for direct winching
$E_d(x,y)$	<i>topological</i>	Maximum extraction distance from the landing site to the nearest truck road	DTM	0-500 m for skidding 0-5000 m for forwarding

220

221 The factor values were linearly rescaled to a common range [0 – 9] (Borgogno-Mondino et al., 2015b),
 222 assuming 0 as the lowest score, in terms of strength (feasibility of the considered logging strategy), and
 223 9 as the highest one, according to a scoring approach that is commonly used in the Multi-Criteria
 224 Decision Making context (Kangas and Kangas, 2005, Mendoza and Prabhu, 2000). These methods have
 225 extensively been employed to support forest management (Kangas and Kangas, 2005, Diaz-Balteiro and
 226 Romero, 2008), and are mainly focused on computing and locating woods that have to be harvested
 227 (Yoshioka and Sakai, 2005, Sacchelli et al., 2013b) or on optimising the decision planning in
 228 consideration of multiple purposes (Pukkala and Miina, 1997, Angelis and Stamatellos, 2004). In the
 229 present work, this approach allowed to obtain a single value summarizing the suitability of the forest
 230 blocks to be harvested (Pauwels et al., 2007). Scores were assigned to the factors according to the
 231 literature on the forestry sector in Italy (Hippoliti and Piegai, 2000, Lubello, 2008, Montorselli et al.,
 232 2010).

233

234 2.3.3 Mapping the harvesting aptitude

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

238 Adopting GIS tools, all the pixels in which at least one factor value had been set to zero were masked
 239 out, as harvesting was not possible in those areas (Azizi et al., 2015). An aptitude map was then
 240 obtained by combining the masked raster layers, using a mathematical formula in which factors with the

241 same weight were assumed (Borgogno-Mondino et al., 2015b). Factors related to the intrinsic features
 242 of the stand ($A_g(x,y)$, $A_s(x,y)$, $S(x,y)$) and those depending on the harvest strategy ($B_d(x,y)$, $B_r(x,y)$,
 243 $E_d(x,y)$) were separately considered. A cumulative relationship was hypothesized among factors of the
 244 same type (intrinsic or harvest dependent), while a multiplicative effect was considered appropriate to
 245 describe the reciprocal influence of the two parts of the formula (Malczewski, 2006).
 246 Since SEM operates in the space domain, the combination of the above mentioned raster layers
 247 according to [1] generates a new raster map in which the aptitude of each cell to be harvested is
 248 measured through a specific strategy, hereafter called “Block Exploitation Aptitude” ($BEA(x,y)$).

249

$$250 \quad \mathbf{BEA}(x,y) = [A_g(x,y) + A_s(x,y) + S(x,y)] \cdot [B_d(x,y) + B_r(x,y) + E_d(x,y)] \quad [1]$$

251

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

253 $A_g(x,y)$ is the block accessibility;

254 $A_s(x,y)$ is the main assortment achievable;

255 $S(x,y)$ is the local slope value;

256 $B_d(x,y)$ is the maximum bunching distance from the felling site to the nearest track or road;

257 $B_r(x,y)$ is the bunching direction, upward or downward to the nearest track or road;

258 $E_d(x,y)$ is the maximum extraction distance from the landing site to the nearest truck road

259

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

265

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 Ribaud, 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

288 harvest costs (Brun et al., 2009). They include on-field surveys, auctions, work safety activities,
289 supervision, financial costs and bank guarantees.

290

291 **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

292

293 The economic and productivity factors were then combined to generate the overall harvesting cost at a
294 block level for any strategy. In other words, the number of workers and machine working hours
295 necessary to accomplish the intervention was calculated for each strategy. These values were multiplied
296 by the corresponding hourly costs, and summed to obtain the overall exploitation cost. In order to define
297 the unitary cost of the harvest (expressed in € m⁻³), this overall amount was related to the harvested
298 timber volume (m³). This allowed different management strategies to be directly compared: thus, the
299 spatial distribution of the strategies and related costs defines exploitation “scenarios” of the area.

300

301 **3 Results and discussion**

302

303 *3.1 Cost-strategy generation*

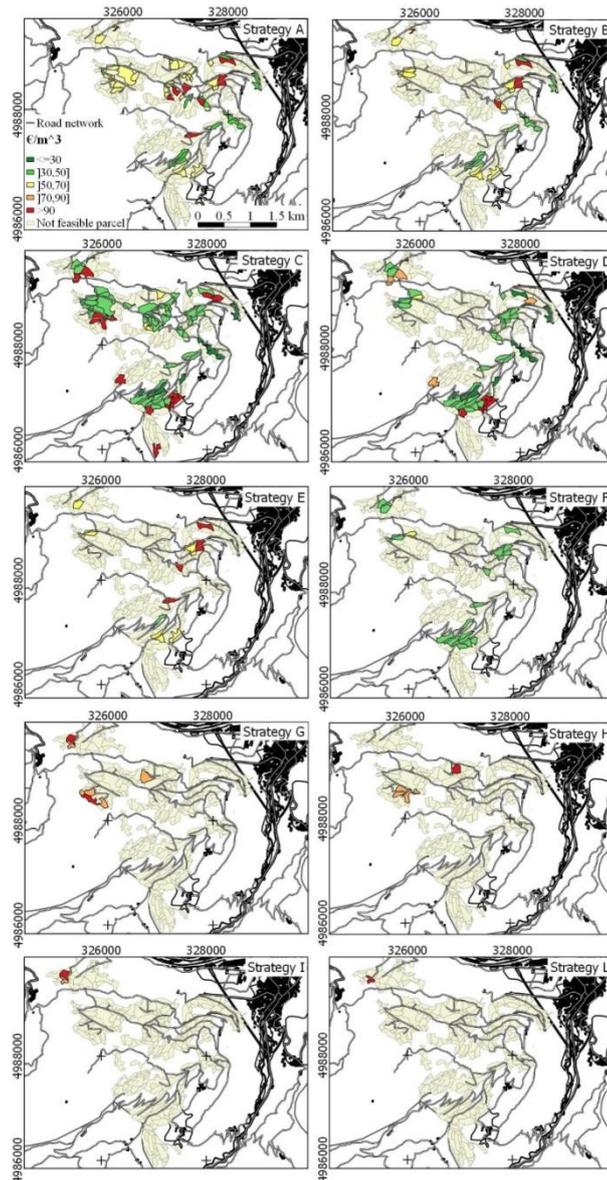
304 Adopting the previously mentioned selection criteria, we found 275 suitable blocks on Mount
305 Cotelivier. Hence, SEM was applied to 366.63 ha, representing 80.46% of the study area (455.62 ha).
306 According to the FMP data, a prescribed yield of 14834 m³ could be obtained from these blocks. The
307 reduction of the harvesting area is mainly due to limitations related to the Map of the Stand Structure: in
308 fact, the reduced size of its blocks occasionally prevented us from scheduling cuts that were large
309 enough to ensure their economic sustainability.

310 Among all the 275 blocks, SEM was able to locate 86 blocks with 226 feasible harvests typologies
311 (31% of the total amount), covering 157.61ha. The total achievable yield from the suitable blocks
312 located by SEM is equal to 6490 m³. This represents 44% of the overall FMP prescribed yield, located
313 on just 34% of the study area. This estimated volume would represent a strong improvement if
314 compared to the current exploitation rate of the area of the 12% (personal communication of the forest
315 consortium). This value, together with the spatially explicit results of the model, can also be considered
316 a useful outcome of the model, since it could support an optimized allocation of the harvests, increasing
317 potentially the timber production. In fact, supplying an overall view of the harvestable area from an
318 economic perspective could help scheduling the simultaneous exploitation of contiguous areas with
319 similar features, with the same strategies, or planning patchwork exploitations in order to reduce their
320 visual impact.

321 Maps showing the suitable areas and correspondent unitary costs (€ m⁻³) of the 10 strategies are reported
322 in Figure 3. The results prove that SEM is able to provide indications about the most suitable strategies
323 for different areas of the compartment according to their features. On the basis of their simple
324 organization, the firsts 4 considered strategies (A, B, C and D) were found to be the most effective and
325 versatile ones; they can be applied to 45, 24, 75 and 44 different forest blocks, respectively. This
326 outcome could be ascribed to the typology of the extraction operation that was adopted, since the use of

327 a tractor has been scheduled for all of them. Strategies E, F, G, H, I and L scored fewer than 40
328 exploitations, and these generally suffered from high operating complexity and a low hourly yield. E
329 and F were found to only be feasible on 10 and 17 blocks, respectively, with the latter ensuring lower
330 harvesting costs, due to its higher mechanization level. These strategies resulted to be suitable for blocks
331 close to the main road network and with a slight slope, due to the characteristics of the used machines.
332 On the other hand, the remaining strategies (G, H, I and L) are only feasible on a few forest stands far
333 from truck roads and with steep slopes. For these reasons, from an overall point of view, the possibility
334 of adopting these strategies may be discarded.

335



336

337

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

338

339

3.2 Performance and limitations of the model

340

The two scenarios that have been generated by SEM at a block level are: a) the location of the most

341

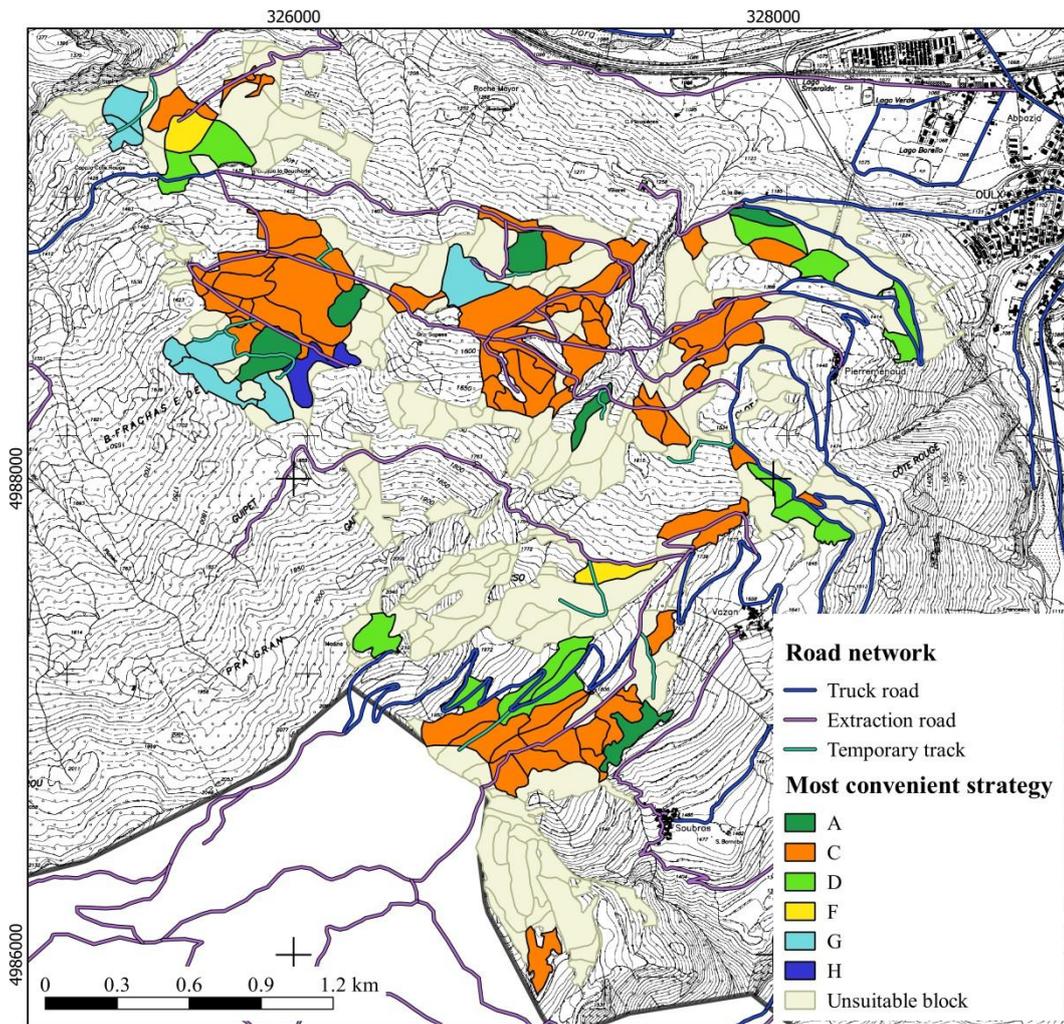
convenient strategy (figure 4); b) the recognition of the lowest unitary harvesting cost, which has been

342

achieved by adopting the most convenient strategy (figure 5). Apart from the main result, a map of the

343

highest *BEA* score for each block has also been generated and archived.



345

346

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

348

349 The strategy that ensures the lowest unitary cost was found by comparing the various generated cost-
 350 scenarios. Method C, which employs machines with low hourly costs and high versatility to operate in
 351 different conditions, has been found to be clearly the most convenient for 59 out of the 86 blocks.
 352 Moreover, the location of several contiguous blocks with the same strategy, as highlighted by SEM,
 353 could represent a further benefit. Planning their exploitation together or in sequence would probably

354 ensure an additional decrease in the harvesting costs, because of the possibility of replicating the same
 355 organization. B, E, I and L always determine higher unitary costs, and therefore do not result to be the
 356 most convenient in any of the scheduled cuts. On the other hand, strategies as G and H resulted the most
 357 convenient ones for most of the blocks (8) where they can be potentially adopted (10). This situation
 358 may be related to the specific features of these areas, which are characterized by steep slopes, difficult
 359 operating conditions but proximity to temporary tracks. These strategies are the only ones that are able
 360 to satisfy the high technical requirements necessary to harvest in those areas.

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

363

364

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

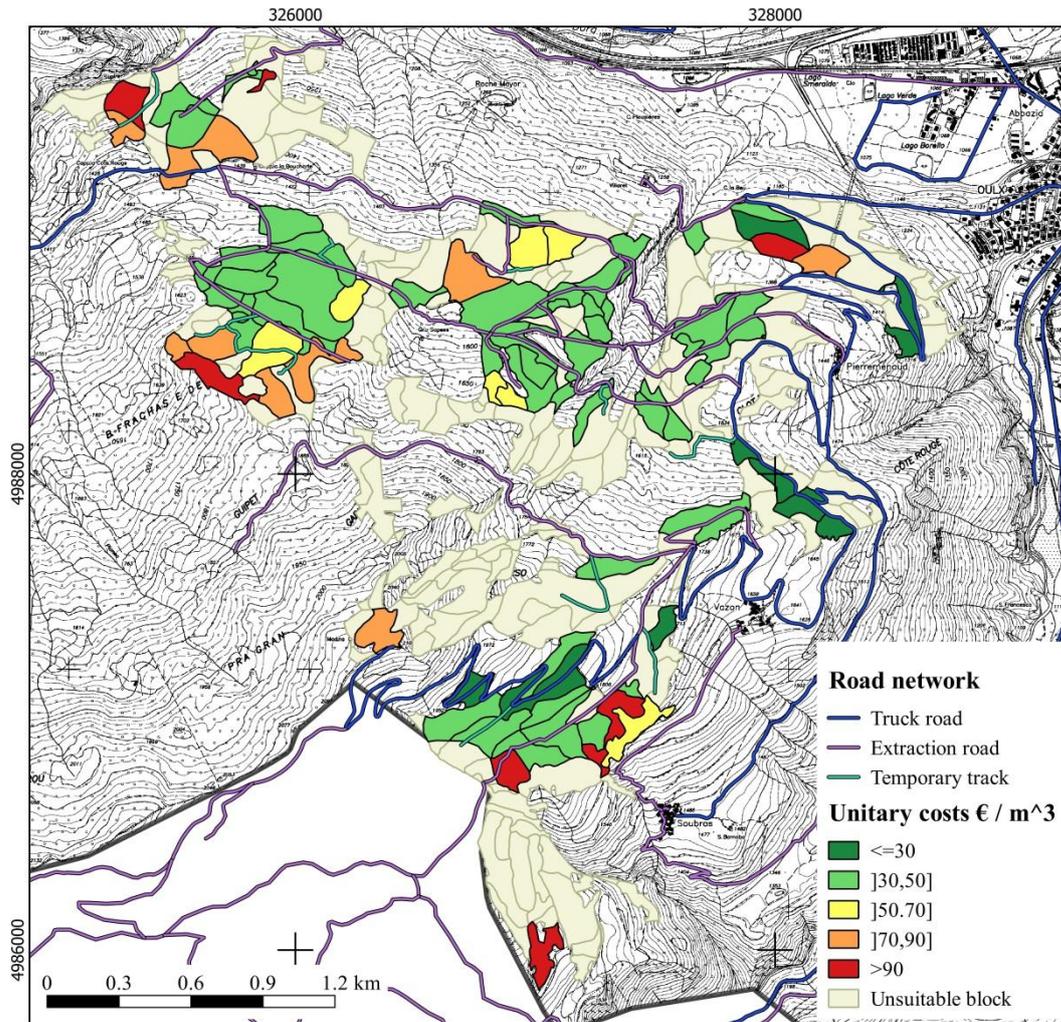
Strategy	Frequency		Total area		Prescribed yield	
	[n]	%	[ha]	%	[m ³]	%
A	6	7.0	13.0	7.8	565	8.7
C	59	68.6	103.0	61.9	4009	61.8
D	11	12.8	26.7	16.0	695	10.7
F	2	2.3	4.9	2.9	194	3.0
G	7	8.1	16.0	9.6	822	12.7
H	1	1.2	3.0	1.8	205	3.2
Total	86	100	166.4	100	6490	100

365

366 Strategy C achieves the best results, for 59 blocks, for an area of 103 ha and more than 4000 m³ of
 367 extracted timber. The second most frequent strategy refers to the blocks where strategy D is the most
 368 convenient, but the corresponding amount of timber volume is generally lower (less than 700 m³ from
 369 11 cuts). The A and G strategies are the most convenient for 13 blocks, where they ensure the
 370 exploitation of more than 1300 m³ of timber. The least frequent strategies are F and H, due to the
 371 unsuitability of employing a skidder in this compartment, and to the specific conditions of the road

372 network. Of the 10 considered strategies, 4 of them are not convenient in any of the blocks. Particularly,
373 for B, E and I the same bunching operation is prescribed, namely the manual logging, so we can
374 suppose this method is, generally, not suitable for the area. This is probably due to its favourable
375 orographic conditions. In fact, low slope values and high assortments dimensions characterized most of
376 the Cotolivier stands, influencing negatively the adoption of this methodology. On the other hand, three
377 of the most frequent strategies (A, C and G) perform timber extraction by tractor and trailer. This
378 element, which is common to all of these successful strategies, can be probably related to the
379 widespread road network of the compartment, where several truck and extraction roads are present.
380 The definition of the most convenient strategies of each block allowed the related unitary harvesting
381 costs to be highlighted. The monetary results were divided into 5 cost classes: ≤ 30 ;]30,50];]50,70];
382]70,90] and $>90 \text{ € m}^{-3}$. Figure 5 shows how these classes are spread over the study area.

383



384

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

387

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

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

393

394
395

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

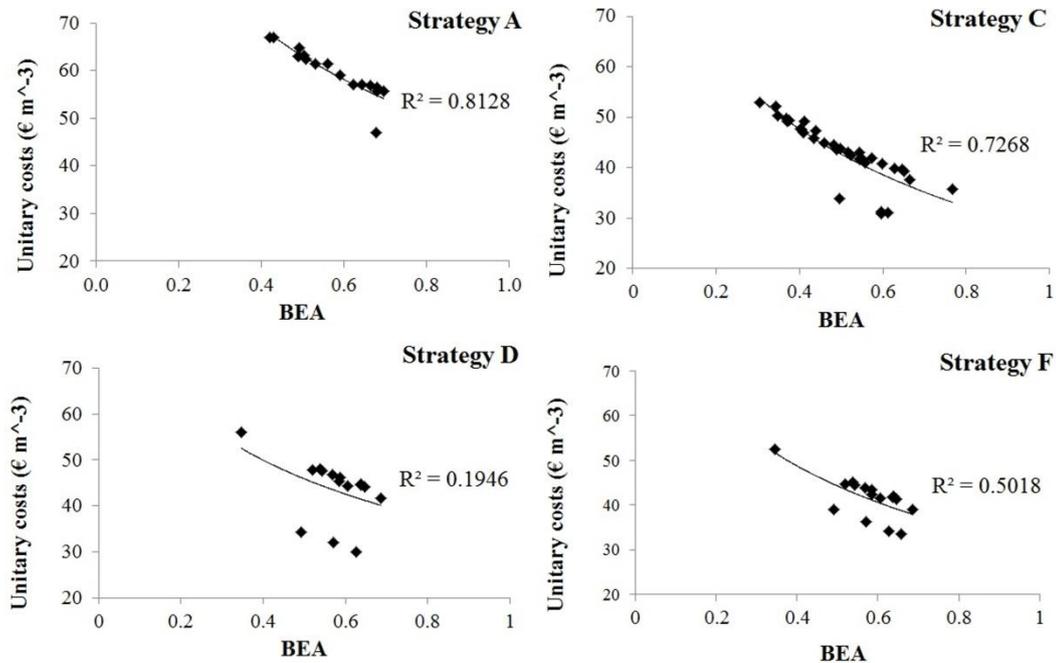
396

397 *BEA* varies from 0.30 to 0.82, with a coefficient of variation of 23.7%. If the *BEA* range is split into
 398 quartiles (Q4: very low *BEA*, from 0.00 to 0.24; Q3: low *BEA*, from 0.25 to 0.49; Q2: high *BEA*, from
 399 0.50 to 0.74; Q1: very high *BEA*, from 0.75 to 0.99), none of the stands belongs to Q4. Strategy C,
 400 which is the most frequent one, shows a *BEA* value ranging from the minimum (0.30) to the maximum
 401 one (0.82) among the possible harvests. Other strategies, such as D and F, present high/very high *BEA*
 402 values and low CV%; differently, G and H strategies are characterized by the lowest mean *BEA* values.
 403 In general, a mean value of 0.54 indicates that the overall destination of the compartment is timber
 404 production, with the most of the stands in Q2.

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

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

416



417

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

419

420 The graphs in figure 6 show that a close relationship emerges between *BEA* and the unitary costs for
 421 strategies with a significant number of harvests (>10). The coefficient of determination (r^2) shows high
 422 values, thus further demonstrating the variation of the unitary costs by *BEA*, even though some outliers
 423 may negatively influence it³. Even the strategies not included in figure 6 are linearly related to *BEA*, but
 424 the limited number of blocks where they can be adopted was not considered enough to ensure
 425 statistically valid results.

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.

426

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

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

- 447 - an operating FMP of the study area is required to map stand structure; in fact, without it, the
448 location of blocks has to be edited manually;

- 449 - contiguous and similar blocks have to be separately considered; the possibility of aggregating
450 them in larger harvests would probably a) increase the overall harvested area, b) reduce
451 exploitation costs and c) optimize compartment management;
- 452 - factors involved in the *BEA* computation were not weighted and values assigned to the
453 conditioning factors suffer from a certain degree of subjectivity. In particular factors selection,
454 value and interaction remain a sensitive point that SEM users have to face. We believe that this
455 uncertainty could be reduced if any information from actual case study in the area were
456 available. According to these, one could consequently modify values in SEM.
- 457 - productivity rates were assumed as linear and directly proportional to *BEA* values; this heavy
458 simplification probably introduces some strong approximations into the evaluation of the correct
459 hourly yields. In fact, some works report that trend cannot be considered perfectly linear
460 (Sacchelli et al., 2013b). It is our intention to focus on this topic in future studies in order to
461 better define the nature of the connection between these two elements;
- 462 - considered period is probably too short; in fact, all the interventions have been hypothesized as
463 being feasible in the short term according to the current stand conditions. This implies that
464 probably more profitable harvests in the medium or long term have be considered, making SEM
465 more robust and general. From this point of view, SEM confirmed to be an effective operational
466 tool for mature forest stands rather than for long-term management purposes.

467

468 Nevertheless, since the aim of this work was to maintain a light framework and generate
469 comprehensible results for users, these issues were deliberately simplified. In spite of these limitations,
470 the monetary values estimated by SEM have proved to be consistent with those estimated autonomously
471 by the forest consortium technicians in this area. The peculiar characteristics of SEM allowed us to

472 reach a level of information useful to forest managers, as needed for an operational tool. Anyway, since
473 the results depend on block classification based on *BEA* values, if any improvement can be achieved, it
474 will necessarily rely on the *BEA* formula.

475 From the users' perspective, SEM allows forest managers to compare different options in order to
476 identify the most convenient one, and to obtain valuable information that can be used to address
477 exploitation strategies at a block level. Moreover, since the design of SEM is based on a multi-criteria
478 approach, further implementations are still possible. In fact, the model can be easily integrated with *ad*
479 *hoc* machines or strategies, with their related costs and productivity rates, in relation to the standard
480 methodologies of the considered area. Anyway, since SEM operates locally, its application to different
481 areas would require a revision of all the involved technical and monetary parameters. The *a-priori*
482 knowledge of the area is thus necessary to ensure a good performance of SEM. Consequently, a strong
483 and continuous dialogue between forest managers and the other stakeholders should be maintained and
484 fostered.

485

486 **4 Conclusions**

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

495 territory is fundamental to achieve reliable outcomes from SEM and address properly management
496 decisions.

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

504

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509

510 **6 References**

- 511 ADAMS, J. D., VISSER, R. J. M. & PRISLEY, S. P. 2003. Modeling Steep Terrain Harvesting Risks Using GIS. *Second*
512 *International Precision Forestry Symposium*. Seattle (WA), USA: Citeseer.
- 513 AKAY, A. E. 2005. Using farm tractors in small-scale forest harvesting operations. *Journal of Applied Sciences Research*, 1,
514 196-199.
- 515 ANANDA, J. & HERATH, G. 2009. A critical review of multi-criteria decision making methods with special reference to forest
516 management and planning. *Ecological Economics*, 68, 2535-2548.
- 517 ANGEHRN, A. A. & JELASSI, T. 1994. DSS reasearch and practice in perspective. *Decision Support Systems*, 12, 267-275.
- 518 ANGELIS, L. & STAMATELLOS, G. 2004. Multiple objective optimization of sampling designs for forest inventories using
519 random search algorithms. *Computers and Electronics in Agriculture*, 42, 129-148.
- 520 ARMITAGE, I. 1998. *Guidelines for the Management of Tropical Forests*, Rome, FAO.
- 521 AZIZI, Z., HOSSEINI, S. M. & YARALI, N. 2015. Mapping the harvesting potential of forest stands using fuzzy sets theory.
522 *Forest Science and Technology*, 11, 147-152.
- 523 BAGNARESI, U., BERNETTI, G., CANTIANI, M. & HELLRIGL, B. 1986. *Nuove metodologie nella elaborazione dei piani di*
524 *asestamento dei boschi*, Bologna, ISEA.

- 525 BERNETTI, I., SOTTINI, V. A., MARINELLI, N., MARONE, E., MENGHINI, S., RICCIOLI, F., SACCHELLI, S. & MARINELLI, A. 2013.
526 Quantification of the total economic value of forest systems: spatial analysis application to the region of Tuscany
527 (Italy). *Aestimum*, 62, 29-65.
- 528 BLANC, S. 2010. *Analisi e valutazioni sull'impiego della manodopera e delle macchine nel comparto agro-forestale*,
529 Grugliasco, DEIAFA.
- 530 BORGHESE, W. & VENZI, L. 1990. Il valore di macchiatico ed il valore di mercato delle piante in piedi. *Linea Ecologica*, 22,
531 47-50.
- 532 BORGOGNO-MONDINO, E., FABIETTI, G. & AJMONE-MARSAN, F. 2015a. Soil quality and landscape metrics as driving factors
533 in a multi-criteria GIS procedure for peri-urban land use planning. *Urban Forestry & Urban Greening*, 14, 743-
534 750.
- 535 BORGOGNO-MONDINO, E., FABRIZIO, E. & CHIABRANDO, R. 2015b. Site Selection of Large Ground-Mounted Photovoltaic
536 Plants: A GIS Decision Support System and an Application to Italy. *International Journal of Green Energy*, 12, 515-
537 525.
- 538 BOTTERO, M., COMINO, E., DURIAVIG, M., FERRETTI, V. & POMARICO, S. 2013. The application of a Multicriteria Spatial
539 Decision Support System (MCSOSS) for the assessment of biodiversity conservation in the Province of Varese
540 (Italy). *Land Use Policy*, 30, 730-738.
- 541 BRANNMAN, L., KLEIN, J. D. & WEISS, L. W. 1987. The price effects of increased competition in auction market. *Review of*
542 *Economics and Statistics*, 69, 24-32.
- 543 BRUKAS, V. & SALLNÄS, O. 2012. Forest management plan as a policy instrument: Carrot, stick or sermon? *Land Use Policy*,
544 29, 605-613.
- 545 BRUN, F., GIAU, B., MAGNANI, C. & BLANC, S. 2009. Guida alla stesura della stima del prezzo di macchiatico. Torino:
546 Università di Torino.
- 547 BÄTZING, W., PERLIK, M. & DEKLEVA, M. 1996. Urbanization and depopulation in the Alps. *Mountain research and*
548 *development*, 335-350.
- 549 CARBONE, F. 2009. Analisi delle componenti che incidono sulle quotazioni dei lotti di castagno all'utilizzazione di fine turno
550 nel comprensorio della bassa Irpinia. *Aestimum*, 50, 17-43.
- 551 CARBONE, F. & RIBAUDO, F. 2005. Stima del valore di macchiatico nel sistema forestale attuale. *Estimo e Territorio*, 68, 9-
552 18.
- 553 CARVALHO-RIBEIRO, S. M., LOVETT, A. & O'RIORDAN, T. 2010. Multifunctional forest management in Northern Portugal:
554 Moving from scenarios to governance for sustainable development. *Land Use Policy*, 27, 1111-1122.
- 555 CHANG, S. J. 1983. Rotation age, management intensity, and the economic factors of timber production: Do changes in
556 stumpage price, interest rate, regeneration cost, and forest taxation matter? *Forest science*, 29, 267-277.
- 557 CHUNG, W., STÜCKELBERGER, J., ARUGA, K. & CUNDY, T. W. 2008. Forest road network design using a trade-off analysis
558 between skidding and road construction costs. *Canadian journal of forest research*, 38, 439-448.
- 559 COPPINI, M. & HERMANIN, L. 2007. Restoration of selective beech coppices: a case study in the Apennines (Italy). *Forest*
560 *Ecology and Management*, 249, 18-27.
- 561 COSTA, A., OLIVEIRA, A. C., VIDAS, F. & BORGES, J. G. 2010. An approach to cork oak forest management planning: a case
562 study in southwestern Portugal. *European Journal of Forest Research*, 129, 233-241.
- 563 DE MEYER, A., ESTRELLA, R., JACXSENS, P., DECKERS, J., VAN ROMPAEY, A. & VAN ORSHOVEN, J. 2013. A conceptual
564 framework and its software implementation to generate spatial decision support systems for land use planning.
565 *Land Use Policy*, 35, 271-282.
- 566 DIAZ-BALTEIRO, L. & ROMERO, C. 2008. Making forestry decisions with multiple criteria: A review and an assessment.
567 *Forest Ecology and Management*, 255, 3222-3241.
- 568 FELARDO, J. & LIPPITT, C. D. 2016. Spatial forest valuation: the role of location in determining attitudes toward payment for
569 ecosystem services policies. *Forest Policy and Economics*, 62, 158-167.
- 570 GASPARINI, P. & TABACCHI, G. 2011. *L'Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio INFC 2005*,
571 Bologna, Edagricole.
- 572 GENELETTI, D. 2004. A GIS-based decision support system to identify nature conservation priorities in an alpine valley. *Land*
573 *Use Policy*, 21, 149-160.
- 574 GIAU, B. 1998. *Manuale per la valutazione della qualità economica dei boschi e per la sua rappresentazione*, Frontone (PU),
575 Edizioni Bosco e Ambiente.

576 GRÊT-REGAMEY, A., BEBI, P., BISHOP, I. D. & SCHMID, W. A. 2008. Linking GIS-based models to value ecosystem services in
577 an Alpine region. *Journal of Environmental Management*, 89, 197-208.

578 HARTL, F., HAHN, A. & KNOKE, T. 2013. Risk-sensitive planning support for forest enterprises: The YAFO model. *Computers
579 and Electronics in Agriculture*, 94, 58-70.

580 HIPPOLITI, G. & PIEGAI, F. 2000. *Tecniche e sistemi di lavoro per la raccolta del legno*, Arezzo, Compagnia delle Foreste.

581 HUNG, S. Y., KU, Y. C., LIANG, T. P. & LEE, C. J. 2007. Regret avoidance as a measure of DSS success: An exploratory study.
582 *Decision Support Systems*, 42, 2093-2106.

583 HUTH, A., DRECHSLER, M. & KÖHLER, P. 2005. Using multicriteria decision analysis and a forest growth model to assess
584 impacts of tree harvesting in Dipterocarp lowland rain forests. *Forest Ecology and Management*, 207, 215-232.

585 HÄYHÄ, T., FRANZESE, P. P., PALETTO, A. & FATH, B. D. 2015. Assessing, valuing, and mapping ecosystem services in Alpine
586 forests. *Ecosystem Services*, 14, 12-23.

587 IPLA 2003. *Norme tecniche regionali di pianificazione silvo-pastorale. Direzione Economia montana e Foreste, Settore
588 Politiche forestali*, Torino, Regione Piemonte.

589 KANGAS, J. & KANGAS, A. 2005. Multiple criteria decision support in forest management - the approach, methods applied,
590 and experiences gained. *Forest Ecology and Management*, 207, 133-143.

591 KÜHMAIER, M. & STAMPFER, K. 2010. Development of a multi-attribute spatial decision support system in selecting timber
592 harvesting systems. *Croatian Journal of Forest Engineering*, 31, 75-88.

593 LINEHAN, P. E. & CORCORAN, T. J. 1994. An expert-system for timber harvesting decision-making on industrial forest lands.
594 *Forest Products Journal*, 44, 65-70.

595 LUBELLO, D. 2008. *A rule-based SDSS for integrated forest harvesting planning*. Doctoral thesis, University of Padova.

596 LUBELLO, D., DEL FAVERO, A. & CAVALLI, R. 2008. Un metodo tecnico-economico come ausilio alla determinazione della
597 ripresa. *L'Italia Forestale e Montana*, 3, 225-240.

598 LÓPEZ TORRES, I., ORTUÑO PÉREZ, S., GARCÍA ROBREDO, F. & FULLANA BELDA, C. 2016. Optimizing the management of
599 uneven-aged *Pinus nigra* stands between two stable positions. *iForest - Biogeosciences and Forestry*, 9, 599-607.

600 MALCZEWSKI, J. 2006. GIS-based multicriteria decision analysis: a survey of the literature. *International Journal of
601 Geographical Information Science*, 20, 703-726.

602 MEI, B., CLUTTER, M. & HARRIS, T. 2010. Modeling and forecasting pine sawtimber stumpage prices in the US South by
603 various time series models. *Canadian Journal of Forest Research*, 40, 1506-1516.

604 MENDOZA, G. A. & PRABHU, R. 2000. Multiple criteria decision making approaches to assessing forest sustainability using
605 criteria and indicators: a case study. *Forest Ecology and Management*, 131, 107-126.

606 MERLO, M. 1993. *Elementi di economia ed estimo forestale-ambientale*, Bologna, Pátron Editore.

607 MONTORSELLI, N. B., LOMBARDINI, C., MAGAGNOTTI, N., MARCHI, E., NERI, F., PICCHI, G. & SPINELLI, R. 2010. Relating
608 safety, productivity and company type for motor-manual logging operations in the Italian Alps. *Accident Analysis
609 and Prevention*, 42, 2013-2017.

610 NAKAHATA, C., UEMURA, R., SAITO, M., KANETSUKI, K. & ARUGA, K. 2014. Estimating harvest costs and projecting
611 quantities of logging residues for small-scale forestry in Nasushiobara, Tochigi Prefecture, Japan. *Journal of
612 Forestry Research*, 25, 965-974.

613 OLSSON, L. 2007. Optimal upgrading of forest road networks: Scenario analysis vs. stochastic modelling. *Forest Policy and
614 Economics*, 9, 1071-1078.

615 PATRONE, G. 1947. Osservazione sul calcolo del prezzo di macchiatico. *L'Italia Forestale e Montana*, 5, 111-114.

616 PAUWELS, D., LEJEUNE, P. & RONDEUX, J. 2007. A decision support system to simulate and compare silvicultural scenarios
617 for pure even-aged larch stands. *Annals of Forest Science*, 64, 345-353.

618 PEARCE, D. W. 1990. An economic approach to saving the tropical forests. *International Institute for Environment and
619 Development*.

620 PETTENELLA, D. 1998. I costi di transazione nella vendita dei lotti boschivi. *QA-La Questione Agraria*.

621 PETTENELLA, D. 2009. Le nuove sfide per il settore forestale. *Mercato, energia, ambiente e politiche. Edizioni Tellus, Roma*.

622 PICCHIO, R., SPINA, R., MAESANO, M., CARBONE, F., MONACO, A. L. & MARCHI, E. 2011. Stumpage value in the short wood
623 system for the conversion into high forest of a oak coppice. *Forestry Studies in China*, 13, 252-262.

624 PIEGAI, F., FRATINI, R. & PETTENELLA, D. 2008. Costi macchina. Confronto fra diversi metodi di calcolo. *Sherwood-Foreste
625 Alberi Oggi*, 145, 9-13.

626 PIEMONTE, R. 2014. Prezzi di riferimento per opere e lavori pubblici nella Regione Piemonte. Torino: Assessorato alla opere
627 Pubbliche, Regione Piemonte, Torino, Italy.

- 628 PLOTTU, E. & PLOTTU, B. 2007. The concept of Total Economic Value of environment: A reconsideration within a
629 hierarchical rationality. *Ecological Economics*, 61, 52-61.
- 630 PROTO, A. R. & ZIMBALATTI, G. 2016. Firewood cable extraction in the southern Mediterranean area of Italy. *Forest Science
631 and Technology*, 12, 16-23.
- 632 PUKKALA, T. & MIINA, J. 1997. A method for stochastic multiobjective optimization of stand management. *Forest Ecology
633 and Management*, 98, 189-203.
- 634 PUSSINEN, A., SCHELHAAS, M. J., VERKAIK, E., HEIKKINEN, E., LISKI, J., KARJALAINEN, T., PÄIVINEN, R. & NABUURS, G. J.
635 2001. Manual for the European forest information scenario model (EFISCEN 2.0). *European Forest Institute,
636 Internal Report*, 5, 1-49.
- 637 PUTTOCK, G. D. 1995. Estimating costs for integrated harvesting and related forest management activities. *Biomass &
638 Bioenergy*, 8, 73-79.
- 639 ROMANO, G., DAL SASSO, P., LIUZZI, G. T. & GENTILE, F. 2015. Multi-criteria decision analysis for land suitability mapping in
640 a rural area of Southern Italy. *Land Use Policy*, 48, 131-143.
- 641 SACCHELLI, S., DE MEO, I. & PALETTA, A. 2013a. Bioenergy production and forest multifunctionality: a trade-off analysis
642 using multiscale GIS model in a case study in Italy. *Applied Energy*, 104, 10-20.
- 643 SACCHELLI, S., ZAMBELLI, P., ZATELLI, P. & CIOLLI, M. 2013b. Biomassfor: an open-source holistic model for the assessment
644 of sustainable forest bioenergy. *iForest-Biogeosciences and Forestry*, 6, 285.
- 645 SECCO, L., FAVERO, M., MASIERO, M. & PETTENELLA, D. M. 2017. Failures of political decentralization in promoting
646 network governance in the forest sector: Observations from Italy. *Land Use Policy*, 62, 79-100.
- 647 SEGURA, M., RAY, D. & MAROTO, C. 2014. Decision support systems for forest management: A comparative analysis and
648 assessment. *Computers and Electronics in Agriculture*, 101, 55-67.
- 649 SERPIERI, A. 1917. Osservazioni sul prezzo di macchiatico. *L'Alpe*, 4, 76-82.
- 650 SESSIONS, J. & SESSIONS, J. B. 1992. *Cost control in forest harvesting and road construction*, Roma, Food and Agriculture
651 Organisation of the United Nations.
- 652 SPINELLI, R., MAGAGNOTTI, N. & FACCHINETTI, D. 2013. Logging companies in the European mountains: an example from
653 the Italian Alps. *International Journal of Forest Engineering*, 24, 109-120.
- 654 SPINELLI, R., MAGAGNOTTI, N. & HARTSOUGH, B. 2006. Raccolta integrata di tondame e biomassa nel taglio a gruppi di
655 fustaie alpine. *L'Italia Forestale e Montana*, 4, 303-316.
- 656 SYNEK, M. & KLIMÁNEK, M. 2015. Spatial modeling of a new technological typification in forestry based on multicriteria
657 evaluation of skidding technologies. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 63,
658 841-852.
- 659 SÁNCHEZ-LOZANO, J. M. & BERNAL-CONESA, J. A. 2017. Environmental management of Natura 2000 network areas
660 through the combination of Geographic Information Systems (GIS) with Multi-Criteria Decision Making (MCDM)
661 methods. Case study in south-eastern Spain. *Land Use Policy*, 63, 86-97.
- 662 THOMPSON, W. A. & WEETMAN, G. F. 1995. Decision-Support Systems for silviculture planning in Canada. *Forestry
663 Chronicle*, 71, 291-298.
- 664 WEST, G. G., MOORE, J. R., SHULA, R. G., HARRINGTON, J. J., SNOOK, J., GORDON, J. A. & RIORDAN, M. P. 2013. *Forest
665 management DSS development in New Zealand*, Zvolen, Slovakia, Technical University of Zvolen.
- 666 YOSHIOKA, T. & SAKAI, H. 2005. Amount and availability of forest biomass as an energy resource in a mountainous region in
667 Japan: A GIS-based analysis. *Croatian Journal of Forest Engineering*, 26, 59-70.
- 668 ZADEH, L. A. 1965. Fuzzy sets. *Information and control*, 8, 338-353.

669

670 **Web references**

671 http://ec.europa.eu/eurostat/web/products-datasets/-/for_area (last visit: 12/01/2016).

672 <http://www.geoportale.piemonte.it/cms/servizi/servizi-di-consultazione> (last visit: 14/01/2016).

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