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This is a pre print version of the following article:

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/149666> since 2022-04-04T21:28:48Z

Published version:

DOI:10.1007/s10342-014-0830-6

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(Article begins on next page)

1 **Renzo Motta^{1*}, Matteo Garbarino², Roberta Berretti¹, Fabio Meloni¹, Antonio**
2 **Nosenzo¹ and Giorgio Vacchiano¹**

3
4 **Development of old-growth characteristics in uneven-aged forests of**
5 **the Italian Alps**

6
7 *¹ Dipartimento di Scienze Agrarie, forestali e alimentari (DISAFA), Università di Torino,*
8 *Grugliasco (TO), 10095, Italy*

9 *² Dipartimento D3A, Università Politecnica delle Marche, Ancona (AN), 60131, Italy*

10 *Corresponding author: Tel: +39 011 670 5538; Fax: +39 011 670 5556; Email: renzo.motta@unito.it

11
12 **Abstract**

13
14 During the last millennia, all forests of the Italian Alps have been heavily
15 affected by human land-use. Consequently, forest structures have been
16 modified and there are no old-growth remains. In the last decades, however,
17 many forests have been withdrawn from regular management, because wood
18 production was unprofitable, and left to develop naturally. At the same time, in
19 currently managed forests, silvicultural systems able to develop or maintain
20 old-growth characteristics are being required. The aim of this paper is to assess
21 the status and developmental dynamics of old-growth characteristics in mixed
22 beech, silver fir, and Norway spruce montane forests of the eastern Italian Alps.

23 We selected along a naturalness gradient (a) three old-growth forests in Bosnia
24 and Montenegro (due to the lack of old-growth forests in the Italian Alps), (b)
25 two forests withdrawn from regular management for at least 50 years, and (c)
26 three currently managed forests. In each forest we analyzed 17 structural
27 attributes, in order to assess their value as indicators of old-growth condition.
28 Old-growth forests were characterized by significantly higher amounts of live
29 and dead biomass, share of beech in the dominant and regeneration layers, and
30 number of large trees. The diameter distribution was best described as a rotated
31 sigmoid, differently from currently and formerly managed forest. We discuss
32 the differences in old-growth characteristics across the management gradient,
33 and use our results to evaluate the effectiveness of retention prescriptions
34 currently applied in the studied regions in maintaining or promoting old-growth
35 structural attributes in managed forests.

36

37 Keywords: forest structure, coarse woody debris, selection system, rotated sigmoid, PCA,
38 retention forestry

39

40

41

42 **Introduction**

43 Old-growth forests are “later stages in forest development that are often compositionally and
44 always structurally distinct from earlier successional stages” (Franklin and Spies 1991). Old-
45 growth forests host plant, fungi and animals that are rare or absent in earlier developmental
46 stages, and are important for regional biodiversity (Bauhus et al. 2009; Burrascano et al. 2013;
47 Keeton 2006; Keeton and Franklin 2005). Moreover, they represent an important reference point
48 for evaluating human impacts on forest ecosystems, and for developing silvicultural systems able
49 to emulate natural processes and fulfil socio-economic goals while maintaining a full range of
50 ecosystem services (Wirth et al. 2009). As the definition implies, old-growth stages can occur
51 also in managed forests that have developed for long periods without human influences and
52 without stand-replacing natural disturbances. The time required for the development of old-
53 growth characteristics in previously managed forests may vary from a few decades to a few
54 centuries, depending on site features (e.g., disturbance regime and history, productivity), and tree
55 species functional traits (e.g. growth rate, longevity, wood decay rate, etc.) (Humphrey 2005;
56 Motta et al. 2010).

57 Starting from the 19th century, silvicultural treatments in central and southern Europe were
58 focused mainly on timber production. “Industrial” production forestry was based mainly on pure,
59 even-aged stands subjected to short rotation periods, i.e., 10-40% of the potential life-span of the
60 main tree species (Bauhus et al. 2009). Only a small part of the forests was subjected to systems
61 based on mixed uneven-aged stands but, also in these systems, wood production was the main
62 purpose. As a consequence, structural attributes typical of later developmental stages are
63 strongly under-represented and, if present, restricted to small and remote forest reserves (Barbati
64 et al. 2012; Peterken 1996).

65 In the last decades a gradual reversal of this trend has been observed, with a decrease in timber
66 removal, and many forests have been withdrawn from management (Castagneri et al. 2010;

67 Motta et al. 2010; Vandekerkhove et al. 2009). At the same time, the scientific community has
68 been advocating for forest management strategies that aim at the restoration of old-growth
69 attributes that would benefit a wealth of taxa that are lacking or threatened in managed forests,
70 even where close-to-nature forestry is applied (Lindenmayer and Franklin 2002; Lindenmayer et
71 al. 2006). Policy frameworks have been set up to facilitate the attainment of this goal (e.g., the
72 Helsinki process) and have in some case led to measurable results (Ammer 1991; Kohler 2010;
73 Vandekerkhove et al. 2011).

74 Despite being an apparent oxymoron, the development of “old-growthness”, i.e., the degree to
75 which structural and functional attributes are similar to those associated to old-growth forests
76 (Bauhus et al. 2009) can be facilitated by appropriate forest management measures. These can be
77 described as either ecological restoration practices (Stanturf and Madsen 2002) e.g., extending
78 thinning rotation periods, regulating stem density and regeneration to match wildlife habitat
79 requirements and mimic the effects of natural disturbances (Bergeron et al. 2007; Silver et al.
80 2013) or retention forestry (Beese et al. 2003; Gustafsson et al. 2010).

81 Gustafsson et al. (2012) defined retention forestry as “an approach to forest management based
82 on the long-term retention of structures and organisms, such as live and dead trees and small
83 areas of intact forests, at the time of harvest”. Retention forestry aims at improving elements of
84 old-growthness pertaining to stand structure, i.e., the quantity and quality of coarse woody debris
85 (CWD), large old trees, and the amount of structural diversity. These elements are not exhaustive
86 of old-growth characters, but provide surrogates for other ecosystem attributes, such as plant or
87 animal diversity (Halpern and Spies 1995; Heilmann-Clausen and Christensen 2003; Kirby and
88 Drake 1993; Lähde et al. 1999; Ódor et al. 2006; Siitonen 2001) with the advantage of being
89 directly manipulated during forest management.

90 The aim of this paper was to identify the structural attributes that contribute to better
91 differentiate between old-growth forests, actively managed forests, and forests withdrawn from

92 regular management (FWRM) in mixed beech (*Fagus sylvatica* L.), silver fir (*Abies alba* Mill.)
93 and Norway spruce (*Picea abies* (L.) Karst.) stands of the Alps and Dinaric mountain ranges. In
94 light of our results, we discuss the effectiveness of current retention forestry aimed at promoting
95 old-growthness in managed stands of the Italian Alps.

96

97 **Material and methods**

98

99 *Study sites*

100 We focused our research on mixed, uneven-aged mountain forests belonging to the association
101 *Piceo-Abieti-Fagetum*. These forests exhibit continuous canopy cover and multilayered vertical
102 structure. In the European temperate forests, old-growth remnants are still present in remote
103 protected areas of Eastern (Parviainen 2005) and South-eastern Europe (Korpel 1995; Nagel et al.
104 2012). They are highly significant for European silviculture, not only because of their natural
105 value, but also because their structure served as a model to develop the silvicultural selection
106 system (Korpel 1995; Leibundgut 1982; Susmel 1980).

107 This study was carried out in eight mixed montane forests of the Italian Alps and of the Dinaric
108 mountains, co-dominated by silver fir, beech and Norway spruce (Fig. 1; Tab. 1). We selected
109 three actively managed forests and two FWRM in the eastern Italian Alps. Ordinary silvicultural
110 management is carried out by harvesting single-tree to small-group maintaining a multilayered
111 and unevenaged stand, and has a limited impact on the landscape. Selection cuttings are repeated
112 every 8-10 years and the main goal of the management is the conservation of the desired
113 diameter distribution and species composition. Santo Stefano di Cadore has been managed by
114 single tree selection since the age of the Republic of Venice (Volin and Buongiorno 1996). In
115 Croviana and Amblar, application of single tree selection is more recent (Wolynski 1998). The
116 two FWRM Val Navarza and Ludrin have developed without direct human influence since 1953

117 and 1962, respectively (Castagneri et al. 2010). Before the abandonment, these forests were
118 managed using a silvicultural selection system but due to their remoteness the cuts were
119 probably less frequent but more intense than in stands closer to a road system. Due to the
120 absence of old-growth forests in the Italian Alps (Motta 2002) we selected three old-growth
121 forests in Bosnia-Herzegovina and Montenegro (Motta et al. In press; Motta et al. 2011; Nagel
122 and Svoboda 2008) about 400 km south-east of the Italian border. Forest cover type, site
123 conditions, and altitudinal range of old-growth forests are similar to the remaining five.

124

125 *Field sampling*

126 In each forest, located within a narrow elevation range (1080 – 1570 m a.s.l.), we selected a
127 sector of 5 – 40 ha (Tab.1), chosen with the help of local foresters in compliance to the following
128 criteria: (a) mixed species composition, i.e., no species with > 70% contribution to total basal
129 area; (b) for old-growth forests, core area or sector of core area in the optimum stage (Korpel
130 1995); (c) for managed forests, management unit(s) in the vicinity of the forest road system; and
131 (d) for FWRM, unmanaged for the longest possible period according to available management
132 plans.

133 In each forest we surveyed the structure by a regular quadrat grid. Grid size varied from 70 to
134 120 m based on the size of the stand, resulting in one sampling point every 0.4 – 1.2 ha of forest.

135 At each sampling point, three types of measurements were carried out (Motta et al. 2011): (1)
136 species, diameter at breast height (dbh) to the nearest 0.01 m, and height (h) to the nearest 0.5 m
137 of all living trees (dbh \geq 7.5 cm) within a 615.5 m² circular plot (radius = 14 m); (2) species of
138 each regeneration tree (h > 10 cm and dbh < 7.5 cm, i.e., seedlings and saplings) within a
139 concentric, 113.1 m² circular plot (radius = 6 m); (3) the diameter of each log crossing a 50 m
140 line (Motta et al. 2006) oriented northward from the centre of each sampling point (orientation
141 bias was assumed to be negligible); and (4) base and top diameter of stumps (height <130 cm),

142 and dbh of snags (height >130 cm) in a 50 x 8 m rectangular plot centred on the previous line.
143 In each site we have measured the height of the overtopping trees in order to estimate the
144 Maximum height (the average of the 5 highest tree ha⁻¹) sensu Susmel (1980).

145
146

147 *Statistical analyses*

148 Volume of living trees, dead standing trees and snags was calculated using local yield tables.
149 Volume of logs was calculated according to line intercept sampling method and the volume of
150 stumps was estimated as a frustum of a cone using diameter at the top and diameter at the ground
151 level (Motta et al. 2006).

152 In each plot we computed 17 structural attributes for living trees and CWD (Tab. 2). We
153 statistically compared structural attributes between management categories (managed, FWRM,
154 old growth) by means of a non-parametric Kruskal-Wallis test, followed by Dunn's post-hoc
155 multiple comparison. In order to identify key gradients of structural variation under different
156 management categories, we carried out a Principal Component Analysis (PCA) on stand
157 structural attributes. Highly correlated attributes (Pearson's $R > 0.75$) were excluded from further
158 analysis (Tab. 2). The statistical significance of PCA axes was tested by random average under
159 permutation, i.e., the average eigenvalue obtained under a randomization of the data matrix,
160 acquired from a randomization test based on eigenvalues. The randomization test was carried out
161 as follows: (1) randomize the values within variables in the data matrix; (2) conduct a PCA on
162 the reshuffled data matrix; and (3) repeat steps 1 and 2 a total of 10000 times. The P -value for
163 each axis and each test statistic was then estimated as: (number of random values equal to or
164 larger than the observed +1) / 1000. If the observed exceeds the average random value, that
165 particular axis is considered to be non-trivial (Peres-Neto et al. 2005). PCA was performed using
166 the function PRCOMP of the R statistical package, version 3.0 (R Core Team 2013).

167 In order to classify and compare dbh distributions, we computed a pooled frequency distribution
168 of tree diameters (midpoints of 5 cm dbh classes) by forest management categories (MAN,
169 FWRM and OG), using data from all living trees and plots (Goodburn and Lorimer 1999).
170 Following \log_{10} transformation, we fitted each frequency distribution by concurrent models
171 based on linear combinations of dbh, dbh^2 and dbh^3 , in order to define its shape (Janowiak et al.
172 2008; Leak 1996). Because the logarithm of zero is undefined, we added 1.0 to the frequency of
173 all dbh classes before log transformation. Among significant models, we selected the model with
174 the highest adjusted R^2 and lowest root mean square error (RMSE) as the best fitting one. The
175 shape of each diameter distribution was determined by examining the significance and sign of
176 model parameters (Alessandrini et al. 2011; Janowiak et al. 2008).

177

178 **Results**

179 Old-growth exhibited significantly higher quadratic mean diameter (QMD), volume of living
180 trees (VOL) ($763 - 1031 \text{ m}^3 \text{ ha}^{-1}$ on average) and volume of coarse woody debris (CWD) ($327 -$
181 $420 \text{ m}^3 \text{ ha}^{-1}$), density of trees with $\text{dbh} > 50$ and $\text{dbh} > 80$ (D50 and D80), volume of snags with
182 $\text{dbh} > 50$ cm (VSNAG50) and volume of logs with diameter > 50 cm (VLOG50) (Tab. 2, Fig. 2).
183 FWRM had the highest tree densities (TPH) and lowest standard deviation of tree diameters
184 (SDD), together with managed forests. The latter had the highest frequency of stumps (STUMP),
185 and lowest basal area (BA), CWD, percent basal area by beech (PERCFASY), percent
186 regeneration by beech (REGFASY), and Shannon diversity index for dbh (HD).
187 PCA of uncorrelated attributes evidenced two significant principal components ($p < 0.001$,
188 Monte Carlo test), that accounted for a cumulative 51,9 % of total variation (Tab. 3; Fig. 3). The
189 type of management gradient was aligned along a direction from managed to old-growth forests
190 of increasing deadwood (VSAG50, VLOG50), increasing incidence of beech (PERCFASY,

191 REGENFASY), density of large tree (D80), and decreasing anthropogenic disturbance (STUMP,
192 VSTUMP), and was relatively orthogonal to HD, QMD and BA .

193 The log₁₀ diameter cumulative distribution of old-growth forests (Fig. 4) was best described as a
194 rotated sigmoid ($p < 0.05$), while it exhibited a concave and a variable shape in managed forests
195 and FWRM, respectively (Tab. 4).

196 The maximum height was between 37-45 m for managed forests, 40-41 m for FWRM and
197 between 46 and 55 m in the old-growth forests.

198

199 **Discussion**

200 *Forest structure*

201 Structural attributes were effective in discriminating managed and old-growth mixed mountain
202 forests of central-southern Europe, consistently with previous research (Boncina 2000; Franklin
203 and Van Pelt 2004; Kuuluvainen et al. 1996; Siitonen et al. 2000). The most significant
204 differences arose from the amount and quality of large woody debris (VSNAG50, VLOG50),
205 and the frequency of very large trees (D80), i.e., variables directly influenced by management
206 intensity.

207 Other indicators associated to the management gradient were maximum height and species
208 composition. The difference in maximum height between managed/FWRM and old-growth
209 forests, i.e., about 5 m, is probably due to the fact that management prevents the trees from a
210 living their complete life-span (Susmel 1980). Species composition, on the other hand, differed
211 between FWRM/old growth and managed forests, especially due to a significantly lower
212 presence of beech in the latter. Even if all stands belonged to the *Abieti-piceion* Br.-Bl. 1939
213 (group F5: mixed beech forests according to the map of potential natural vegetation in Europe)
214 (Bohn et al. 2003), past management in the Alps resulted in a negative selection on beech, due to
215 a preference for spruce and fir that had a more valuable timber (Poldini and Bressan 2007). This

216 is in contrast to the observed current trends observed in most old-growth forests of central-
217 eastern Europe where there is long-term quantitative increment of beech and a quantitative and
218 qualitative reduction of the conifers (Diaci et al. 2011; Keren et al. 2014). In forests left
219 unmanaged for some decades, beech has started to increase its share in the lower diameter
220 classes, even if large individuals are still lacking compared to old-growth forests (Fig. 5). A
221 similar trend occurred in the regeneration layer (regeneration density, Tab. 2). Current
222 silvicultural management protocols have abandoned negative selection on beech, but the low
223 number of seed trees, as a legacy of past management, implies that these stands still experience a
224 scarcity of beech in the intermediate and regeneration layers as well. It is possible, however, that
225 the quantity and quality of coarse woody debris would differ between beech-rich (old-growth)
226 and beech-devoid forests (FWRM and managed), due to the highest production of large branches
227 and fastest decay rate of the broadleaf species (Chirici et al. 2014) as opposed to the conifers.

228 Old-growth forests were represented as a distinct group on the ordination plot, that expressed
229 gradients of large tree density, biomass, specific composition, quantity of deadwood (logs and
230 snags) and incidence of beech. The scattered distribution of old-growth sampling points on the
231 ordination plot revealed a high heterogeneity of forest structure, as opposed to the smaller
232 variability of structural attributes in formerly and currently managed forests.

233 On the other hand, there was a wide overlap of the structural data coming from managed forests
234 and FWRM. This is mainly due to the relatively short period that FWRM have spent without
235 direct human influence, about 50 and 60 years respectively. Mature managed stands are expected
236 to take about one century to reach amounts of deadwood and large living trees about half of
237 those found in old-growth (Christensen et al. 2005; Nilsson et al. 2002; Vandekerkhove et al.
238 2009). FWRM differed from managed forests mainly for increased tree density and CWD
239 volume (Sitzia et al. 2012). The amount of CWD in FWRM was in line with what is expected in
240 a forest that was left unmanaged for about 50 years (Meyer and Schmidt 2011; Motta et al. 2006;

241 Vandekerckhove et al. 2009), and twice as much as in managed forests, even though CWD in the
242 studied managed forests was already much higher than the Italian average for similar forests, i.e.,
243 $7 \text{ m}^3 \text{ ha}^{-1}$ for beech, $16 \text{ m}^3 \text{ ha}^{-1}$ for spruce, and $21 \text{ m}^3 \text{ ha}^{-1}$ for silver fir-dominated forests (INFC
244 2005). At the current developmental stage, mortality in FRWM was mainly concentrated in
245 small and intermediate diameters, and only sporadically affected the dominant layer.
246 Consequently, the total amount of CWD and the density of large snags and logs were still very
247 low if compared with old-growth forests (for FWRM and old-growth $70 - 85$ vs $327 - 420 \text{ m}^3$
248 ha^{-1} of CWD and $1 - 2$ vs $19 - 28$ snags $>50 \text{ cm dbh ha}^{-1}$). However, CWD in both managed and
249 abandoned forests in this study are higher than $20 - 30 \text{ m}^3 \text{ ha}^{-1}$, i.e. the proposed threshold to
250 safeguard the complete spectrum of species that rely on deadwood (Angelstam et al. 2003;
251 Müller and Bütler 2010). The density of very large trees ($\text{dbh} > 80 \text{ cm}$) was higher in the managed
252 forests than in FWRM ($0-10$ vs $0-3 \text{ ha}^{-1}$). This is due both to recent retention forestry policies in
253 managed forests and to the fact that before the abandonment, due to their remoteness, the last
254 cuts were probably in between from a selection and a high-grading system. In any case the
255 density of very large trees of both managed and FWRM was very low if compared with old-
256 growth forests ($18-37 \text{ ha}^{-1}$)

257 Another important difference between the three management categories was the shape of the
258 diameter distributions (Fig. 4; Tab. 4). Traditionally, the diameter distribution of both managed
259 and unmanaged uneven-aged forests has been represented as reverse J-shaped, or negative
260 exponential (de Liocourt 1898; O'Hara and Gersonde 2004). Recent research has revealed that,
261 for primary forests, it can be better modeled by a rotated sigmoid (Alessandrini et al. 2011; Goff
262 and West 1975; Janowiak et al. 2008). Our results confirmed the latter hypothesis, but not the
263 former, as the log-transformed diameter distribution of managed forests was found to fit a
264 concave function. The concave shape is the result of a deficit in intermediate size classes, with
265 the addition of which it would be classified as a rotated sigmoid. Emergence of a concave

266 distribution in our managed forests may be explained by retention forestry prescriptions, albeit
267 very recent, that aimed at the conservation of cavity-nesting birds by increasing the number of
268 large diameter trees. Similar studies have pointed out that the concave distribution is evident at
269 small spatial scales (<0.8 ha) (Janowiak et al. 2008) as a result of small gap dynamics or, in our
270 case, to single tree selection practices. Old-growth stands are characterized by an ongoing gap-
271 phase dynamics (Bottero et al. 2011; Kucbel et al. 2010) that can explain the coexistence of
272 multiple structural stages in the same forest (hence the large scatter of OG points on Fig. 3).
273 Conversely, in forests currently or formerly managed for timber, natural disturbances have been
274 replaced by anthropogenic intervention, which may have led to a much greater structural
275 homogeneity (Attiwill 1994) and to a different shape of the diameter distribution. Besides the
276 studied structural parameters the tree spatial pattern, analysed in large permanent plots (Lingua
277 et al. 2011) is another important indicator of old-growthness, differentiating more or less random
278 structures resulting from active management, from a gradient of clumping and subsequent
279 mortality-induced regularization from ongoing competition in natural gaps typical of unmanaged
280 and old-growth forests (Moeur 1997).
281 Finally, the variable shape of FWRM diameter distribution may be a consequence of the
282 structural re-organisation that forests managed for a long period of time experience after the
283 abandonment.

284

285 *Retention forestry policies*

286 Notwithstanding some concerns about costs, unwanted negative impacts, and social acceptability,
287 foresters and stakeholders have recently increased their awareness about the importance of
288 conserving biodiversity in regular forest management activities and it has been common practice
289 to leave dead and living trees for biodiversity purposes (Gustafsson et al. 2012; Larrieu et al.
290 2012).

291 All the managed forests were, from a silvicultural point of view, overstocked. The increment
292 maximization and long-term structural stability in mixed spruce-fir-beech forests should be
293 attained at around $350 - 400 \text{ m}^3 \text{ ha}^{-1}$ (Schütz 1996), while the observed volumes ($453 - 622 \text{ m}^3$
294 ha^{-1}) were much higher. The management regime in selection forests does not depend only on
295 theoretical approaches but it is strongly influenced by social and economical conditions.

296 Like most aspects of forest legislation in Italy, the strictness of retention rules in the alpine
297 region varies on a regional/autonomous province basis, and whether or not forests are within a
298 Natura 2000 protected area (Tab. 5). The rules are stricter in regions, like Piedmont or Lombardy,
299 where most traditional silvicultural systems are coppices based on a rotation of 20-30 years. The
300 range of required retention is wider, but at the same time the rules are not so strict, in regions
301 rich in high forests, where there is a long tradition of close-to-nature and sustainable forest
302 management.

303 However the quantity and quality of retention of old-growth elements that would be adequate for
304 conservation purposes is not known. On one hand, current prescriptions require the retention of
305 minimal densities ($0 - 5 \text{ ha}^{-1}$) of ageing or standing dead trees (Tab. 5). This figure is
306 comparable to what is being prescribed in actively managed forests of western and central
307 Europe (e.g., Flanders: 4% of total stock; Baden-Wurttemberg: 15 trees every 3 ha) (Spielmann et
308 al. 2013; Vandekerkhove 2013) but far below the levels detected by this study in unmanaged and
309 old-growth forest, and lower than what is recommended for the conservation of specific
310 organisms such as woodpeckers (Bütler 2003).

311 Moreover, the prescriptions ignore key components of habitat and ecosystem functioning, such
312 as structural diversity or deadwood on the ground and it is not known what quantity and quality
313 of retention of old-growth elements would be adequate for the set conservation purposes, i.e., the
314 habitat requirements of plant and animal species to be protected at each site are often unclear
315 (Paillet et al. 2010)

316 Finally, retention strategies at the tree or stand scale should be supported by prescriptions on a
317 larger scale, such as restoration of less natural forest ecosystems and establishment of set-aside
318 areas (forest reserves), aiming at restoring landscape connectivity and building an effective
319 biodiversity network (Bengtsson et al. 2000; Fahrig 2003; Lindenmayer and Franklin 2002).

320

321 **Conclusions**

322 Both managed and FWRM mixed spruce-fir-beech forests of the Italian Alps have currently few
323 old-growth structural elements. An increase of such elements is desirable in order to improve
324 ecosystem functioning and biodiversity conservation.

325 Live biomass and large-sized living trees, CWD biomass in different decay stages, large snags,
326 and basal area of beech were the most important variables discriminating the three management
327 categories. This result is aligned to the current body of literature, but nonetheless contains
328 valuable information for future studies on indicators of biodiversity.

329 The establishment of retention forestry measures is relatively recent, but despite their limited
330 scope and strictness, some effects may be achieved relatively quickly, as we observed in forests
331 where management was abandoned in the last decades, i.e., an increment of large trees and CWD,
332 and a potential shift from negative exponential to concave diameter distribution. On the other
333 hand, 50 years of withdrawal from management are obviously not enough to approximate the
334 degree of old-growthness found in pristine reference forests. According to Nilsson et al. (2002),
335 in boreal forests 100 year without management may be enough to hide the traces of past cutting
336 (even if the structure of the forests may be still influenced by the past human disturbances). This
337 is not the case in the studied mixed forests of the Alps, where the development of old-growth
338 structural characteristics is very slow, and where past management has probably introduced a
339 temporal lag in this process. At the same time, our findings highlight additional stand attributes
340 to be targeted by future retention forestry policies. While in the past the traditional selection

341 management was oriented mainly towards maintaining the targeted structure and composition,
342 our results evidenced that tree and CWD retention and the CWD decay processes are important
343 for the restoration of the biological diversity. Monitoring and research need to be enhanced in
344 order to modify existing silvicultural measures based on this evidence, and assess their effect
345 through time.

346

347 **Funding**

348 This work was partially supported by the Autonomous Province of Trento and by the Friuli
349 Venezia Giulia Autonomous Region (Research on forests withdrawn from regular managements).
350 Spot Image Inc., through Planet Action Program domain “Forest and deforestation,” provided
351 funding for the research in the Bosnia-Herzegovina and Montenegro old-growth forests by
352 donating satellite imagery and image processing systems.

353

354 **Acknowledgements**

355 The authors wish to thank Alessandro Wolynski (Autonomous Province of Trento), Franca de
356 Ferrari (Piemonte Region), Damiano Penco and Luca Iacopi (Liguria Region), Maurizio
357 Dissegna, Giovanni Carraro and Ivan Davide Orlando (Veneto Region), Enrico Calvo (ERSAF,
358 Lombardy Region) for useful information and comments regarding retention forestry, Giuseppe
359 Menegus (Regione Veneto), Fabio Angeli, Paolo Zorer and Maurizio Mezzanotte (Autonomous
360 Province of Trento) for useful information and for the field support in the three managed forests,
361 Ivan Bjelanovic, Milic Čurović, Srdjan Keren and Vojislav Dukić for the field support in the old-
362 growth forests. We thank the anonymous reviewers for their careful reading of our manuscript
363 and their many insightful comments and suggestions.

364

365 **Conflict of interest statement**

366 None declared.

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572 **Table and Figure captions**

573

574 **Table 1** Characteristics of the eight study sites.

575

576 **Table 2** Forest structural characteristics of the eight study sites.

577

578 **Table 3.** Principal component loadings for the first two principal components for the eight study
579 areas. Codes in Table 2.

580

581 **Table 4** Signs (+/-) of significant coefficients (dbh, dbh² and dbh³) in polynomial regression
582 models used to determine diameter distribution shape (Janowiak et al. 2008) in uneven-aged
583 forests. All the models grouped in the management categories were significant ($p < 0.001$) and
584 their performance was compared through goodness of fit indices: adjusted R² (Adj. R²), root
585 mean square error (RMSE), Akaike information criterion (AIC) and Sum of squares due to error
586 (SSE).

587

588 **Table 5** Retention forestry in northern Italian regions and autonomous provinces according to
589 current regional/provincial laws

590

591 **Figure 1** Map of the study area. Location of sites (AMB - Amblar, CRO - Croviana, CAD -
592 Santo Stefano di Cadore, LUD – Ludrin, NAV - Navarza, LOM - Lom, BIO - Biogradska gora,
593 PER – Perućica) and management category (triangles: old growth; circles: FWRM; squares:
594 managed).

595
596 **Figure 2** Boxplots of 17 structural attributes in currently managed (MAN) forests, forests
597 withdrawn from regular management (FWRM), and old-growth (OG). Groups with identical
598 letters are not significantly different from each other ($p < 0.05$).

599
600 **Figure 3** Principal component analysis (PCA of 207 plots) of structure surveyed in the study
601 sites. Arrows represent selected forest structure descriptors (see Tab. 2 for codes). Triangles: old
602 growth (og); circles: withdrawn from regular management (fwrn); squares: managed forests
603 (man).

604
605 **Figure 4** Diameter distributions in managed forests (MAN), forests withdrawn from regular
606 management (FWRM), and old-growth (OG).

607
608 **Figure 5** Relative frequency (average number of trees ha^{-1}) for increasing size classes in
609 managed forests (MAN), forests withdrawn from regular management (FWRM), and old-growth
610 (OG).

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615 **Tables**
 616
 617 Tab. 1
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Site	Code	Location	Area (ha)	n. plots	Altitude (m a.s.l.)	Slope (°)	Management category
Amblar	AMB	Italy, TN	5	13	1150-1220	5-25	Managed (single tree selection)
Croviana	CRO	Italy, TN	9	14	1220-1290	0-20	Managed (single tree selection)
Santo Stefano Cadore	CAD	Italy, BL	15	21	1080-1190	0-29	Managed (single tree selection)
Ludrin	LUD	Italy, TN	27	22	1250-1350	0-30	Withdrawn from regular management since 1962
Val Navarza	NAV	Italy, UD	37	33	1300-1570	12-34	Withdrawn from regular management since 1953
Lom	LOM	Bosnia-Herzegovina	40	40	1250-1520	0-40	Old-growth forest
Perućica	PER	Bosnia-Herzegovina	32	32	1340-1510	4-40	Old-growth forest
Biogradska gora	BIO	Montenegro	30	30	1210-1450	0-35	Old-growth forest

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623 Tab. 2
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625 Attached file
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627

Statistical parameters	PC1	PC2	
<i>% of variance</i>	34.32	17.57	628
<i>cumulative % of variance</i>	34.32	51.89	629
<i>p</i>	0.001	0.001	630
BA	-0.36	0.41	631
D80	-0.40	0.20	
HD	-0.27	0.32	632
QMD	-0.39	0.30	
REGEN	-0.01	-0.01	633
STUMP	0.39	0.31	
VLOG50	-0.31	-0.25	634
VSNAG50	-0.27	-0.12	
VSTUMP	0.26	0.21	635
PERCFASY	-0.13	-0.56	
REGFASY	-0.28	-0.25	636

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639 Tab. 3

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648 Tab. 4
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Management category	SSE	AIC	RMSE	Adj. R ²	dbh	dbh ²	dbh ³	Distribution shape
AMB	15.901	224.432	0.195	0.933	ns	ns	+	Unclassified
CAD	19.417	226.948	0.193	0.946	-	ns	ns	Negative Exp.
CRO	13.747	222.598	0.204	0.915	ns	+	+	Unclassified
Managed	13.601	222.464	0.121	0.971	-	ns	+	Concave
LUD	19.791	227.188	0.214	0.935	ns	ns	+	Unclassified
NAV	17.300	225.494	0.157	0.960	ns	+	+	Unclassified
FWRM	14.692	223.436	0.132	0.967	ns	+	+	Variable
LOM	11.997	220.884	0.148	0.949	-	ns	ns	Negative Exp.
PER	8.889	217.107	0.127	0.949	-	+	-	Rotated Sig.
BIO	8.054	215.865	0.168	0.902	-	ns	ns	Negative Exp.
Old-growth	8.737	216.890	0.086	0.976	-	+	-	Rotated Sigmoid

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Region/Province	Retention forestry measures All forests	Retention forestry measures Natura 2000 forests	Other	Notes
Piemonte	Some ageing trees (no definite number and no marking) advised as a "good practice"	Living ageing trees (quantity not defined) and 2 dead trees ha ⁻¹ (snags or logs) if present. Additional retention measures scheduled locally for Natura 2000 forests		Conservation of dead or decaying habitat trees is advised in Natura 2000 forests
Valle d'Aosta Autonomous Region		Retention measures scheduled locally for Natura 2000 forests		Conservation of dead or decaying habitat trees is advised in Natura 2000 forests
Liguria		5 dead trees ha ⁻¹ , if present. Other additional measures scheduled locally for Natura 2000 forests		Conservation of "biodiversity islands", old trees, biodiversity trees is advised in Natura 2000 forests
Lombardia	2 living ageing trees ha ⁻¹ (marked, the trees must be replaced in case of death)	Retention measures scheduled locally for Natura 2000 forests		Conservation of dead or decaying habitat trees is advised in Natura 2000 forests
Bolzano Autonomous Province	Some ageing trees (no definite number and no marking).	Retention measures scheduled locally for Natura 2000 forests		According to the provincial forest rules some ageing trees, should be retained for biodiversity purposes in all the forests. Conservation of dead or decaying habitat trees is advised in Natura 2000 forests
Trento Autonomous Province	Some ageing trees (no definite number and no marking).	Retention measures scheduled locally for Natura 2000 forests		According to the provincial forest rules habitat trees, old or monumental trees, rare species should be retained for biodiversity purposes in all the forests. Conservation of dead or decaying habitat trees is advised in Natura 2000 forests
Veneto		Retention measures scheduled locally for Natura 2000 forests	Public funding (up to 200 € ha ⁻¹) for owners that agree to preserve large living trees and dead trees (marked)	Conservation of dead or decaying habitat trees is advised in Natura 2000 forests
Friuli Venezia Giulia Autonomous Region	Some ageing trees (no definite number and no marking).	2 living trees (dbh > 50 cm if present) and 1 dead tree (dbh > 40 cm if present) ha ⁻¹ . Other additional measures scheduled locally for Natura 2000 forests		According to the regional forest rules some ageing trees, should be retained for biodiversity purposes. Conservation of dead or decaying habitat trees is advised in Natura 2000 forests