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**Site and stand effects on coarse woody debris in montane mixed forests of Eastern Italian Alps**

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1 **Legacies of past forest management on present deadwood in montane mixed forests of**  
2 **Eastern Italian Alps**

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35 **Abstract**

36 The role of deadwood on biodiversity conservation of forest ecosystems is widely recognised.  
37 Interest on deadwood has increased in the last years, and forest management policy regards  
38 deadwood as indicator of sustainable forest management.

39 This study took place in mixed montane forests in Eastern Italian Alps. The objective was to  
40 determine how past forest management, topography and forest structure influence deadwood  
41 accumulation. 124 sampling points were established in four Forest Reserves, where time of non-  
42 intervention ranges from 12 to more than 50 years. A multivariate analysis was performed to  
43 investigate the connections between forest stand characteristics and deadwood.

44 Coarse woody debris (CWD) volume in the reserves was similar to other recently-unmanaged  
45 forests in central Europe. Both stand characteristics and topographic factors determined CWD  
46 distribution. Basal area of living trees and human impact emerged as the most important factors.  
47 These aspects are connected with the input (density-dependent mortality) and the output  
48 (harvesting) of deadwood in the stand. In the next decades we expect an increase of deadwood, due  
49 to density-dependent mortality and disturbances. However, many decades in absence of human  
50 interventions are probably required to reach amount of deadwood similar to those in old-growth  
51 forests.

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58 **Keywords** Alps; coarse woody debris; human impact; mixed forest; montane forest; multivariate  
59 analysis.

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69 **1. Introduction**

70 Deadwood is an important component in the functioning of the forest ecosystem, as it plays an  
71 important role in biodiversity, trophic chains, forest natural regeneration, nutrient cycles and overall  
72 carbon storage (Harmon et al., 1986; Franklin et al., 1987; Jonsson and Kruys, 2001; Laiho and  
73 Prescott, 2004; Luysaert et al., 2008). During the last decades research focused on the assessment  
74 of deadwood amount in forests have been common in North America (Spies and Franklin, 1988;  
75 McCarthy and Bailey, 1994; Sturtevant et al., 1997; Clark et al., 1998) and northern Europe  
76 (Sippola et al., 1998; Jonsson, 2000; Siitonen et al., 2000; Krankina et al., 2002). However, in  
77 central and southern Europe deadwood has received less attention (Bretz Guby and Dobbertin,  
78 1996; Marage and Lemperiere, 2005; Motta et al., 2006; Lombardi et al., 2008).

79 In central and southern Europe human pressure has affected forest dynamics since prehistoric times  
80 (Farrel et al., 2000; Motta and Nola, 2001; Winter et al., 2010), peaking in the last century. In most  
81 regions of the Alps anthropogenic impact has been very severe because forests have been used for  
82 timber, fuel wood, forest litter, deadwood, branches and even small twigs collection and were  
83 subjected to grazing (Bürgi and Gimmi, 2007; Gimmi et al., 2008). During recent decades the  
84 anthropogenic impact on forests has considerably diminished, and in eastern Italian Alps a large  
85 part of forests have been withdrawn from regular management since the early 1950s (Martinis,  
86 1990; Farrell et al., 2000; Lehringer et al., 2003). Moreover, the public attitude towards forests and  
87 forestry has dramatically changed. Past management was concentrated on what was being extracted  
88 from the forest, whereas current management emphasizes what is being left (Kohm and Franklin,  
89 1997). In this context, quantity and quality of coarse woody debris (CWD) are regarded as  
90 important structural indicators of naturalness and biodiversity (Corona et al., 2003; MCPFE, 2003;  
91 Jönsson and Jonsson, 2007), providing information on the intensity of past human disturbances and  
92 closeness to old-growth condition (Stokland, 2001; Woodall and Nagel, 2006).

93 The amount of deadwood is determined by its inputs and outputs in the forest (Siitonen, 2001).  
94 Deadwood natural accumulation is influenced by disturbance regime, climate, tree species  
95 composition, tree size (von Oheimb et al., 2007), stand succession stage, stand structure (Siitonen et  
96 al., 2000), topography (Rubino and Mc Carty, 2003), decomposer organisms (Harmon, 2009).  
97 Besides, forest management can affect deadwood input. Silvicultural interventions alter tree species  
98 composition and forest structure, reducing competition intensity and mortality, and removing  
99 weakened trees having the highest potential to die (Siitonen et al., 2000 Rouvinen et al., 2002).

100 Short rotation loggings interrupt natural stage development, preventing forest ageing and deadwood  
101 formation (Duvall and Grigal, 1999; Currie and Nadelhoffer, 2002; Vandekerkhove et al., 2009).  
102 Moreover, a direct removal of dead wood can occur to obtain fire wood and to reduce wildfire and

103 pathogen attack risk (Wolynski, 2001). Therefore, deadwood quantities are normally lower in  
104 managed than in unmanaged forests (Gibb et al., 2005; Müller-Using and Bartsch, 2009;  
105 Vandekerkhove et al., 2009).

106 The present study was carried out in four Forest Reserves of the eastern Italian Alps located in the  
107 montane belt (1000-1600 m a.s.l.) where mature stands have been left unmanaged between 12 and  
108 50 years. The vegetation type is a mixed forest of European beech (*Fagus sylvatica* L.), silver fir  
109 (*Abies alba* Mill.) and Norway spruce (*Picea abies* (L.) Karst.). Even if past anthropogenic impact  
110 has affected forest structure the native species are still present and regenerate naturally.

111 The aim of our analysis was to assess the legacies of past logging and stand characteristics on  
112 deadwood. Main research questions were: (1) what is the current volume of deadwood in mixed  
113 *Fagus-Abies-Picea* forests withdrawn from regular management in eastern Italian Alps? (2) What is  
114 the influence of former management, topography, and forest structure on quantity and quality of  
115 deadwood?

116

## 117 **2. Methods**

### 118 **2.1. Study areas**

119 The study took place in four Forest Reserves located in eastern Italian Alps (Val Novarza, Val  
120 Pontebbana and Col Piova in Friuli-Venezia Giulia Region, Ludrin in Trentino-Alto Adige Region,  
121 Fig. 1) with an elevation range from 1020 to 1630 m a.s.l. The predominant soil type is cambisol,  
122 developed on carbonatic substrate except for Val Pontebbana where a silicic substrate was  
123 dominant. Climate regime is similar among the reserves. Val Novarza and Val Pontebbana belong  
124 to “mesalpic district” with mean annual temperature averaging 8 °C, and annual precipitation  
125 averaging 1600 mm (Del Favero et al., 1998). Ludrin has a similar mean annual temperature, while  
126 annual precipitation differs from the other reserves averaging 1300 mm. Col Piova lies in the  
127 “esalpic district”, with mean annual temperature of 11 °C and precipitation of 1700 mm/year (Del  
128 Favero et al., 1998). In all the study sites the precipitation peaks are in spring (May - June) and  
129 autumn (November).

130 Stands are characterized by Norway spruce (*Picea abies* (L.) Karst.), silver fir (*Abies alba* Mill.)  
131 and European beech (*Fagus sylvatica* L.), representing the main species in Italian Alps montane  
132 forests. Other species (*Larix decidua* Mill., *Acer pseudoplatanus* L., *Sorbus aucuparia* L., and other  
133 montane broadleaf species) occur sporadically.

134 Val Novarza Forest Reserve (37 ha; latitude 46°27' N; longitude 12°46' E) is located at an altitude  
135 from 1300 to 1570 m a.s.l, and predominant aspect is west and north-west. Intensive selection  
136 cutting involving both beech and conifers occurred during 1940s, ending in 1953-1955 (forest

137 management plan archive). No other activities were recorded in successive period, apart from a 37.5  
138 m<sup>3</sup> cut in 1997 in the lower part of the reserve. Val Pontebbana Forest Reserve (37.6 ha; latitude  
139 46°32' N; longitude 13°10' E) is east exposed, and altitude varies from 1240 to 1630 m a.s.l. The  
140 upper part was managed with group or individual selection cutting, and the last logging was  
141 conducted in the early 1960s (forest management plan archive). In the central part, last cutting was  
142 performed in 1982, while in the lower part intense selection cutting have been made until 1996. Col  
143 Piova Forest Reserve (36 ha; latitude 46°04' N; longitude 12°26' E) is predominantly west and  
144 north-west exposed, and altitude varies from 1020 to 1200 m a.s.l. At higher elevation, cutting  
145 brought to an end in 1960, while the rest of the forest was logged until 1989. Ludrin Forest Reserve  
146 (26.5 ha; latitude 46°07' N; longitude 10°56' E) occupies a part of a small valley north-south  
147 oriented, at an altitude from 1250 to 1350 m a.s.l. Several cutting occurred during 1950s, and the  
148 last silvicultural operations were performed in 1962. Comparison of ipsometric curves (tree  
149 diameter vs. tree height) of the three principal species showed a similar site productivity among the  
150 four reserves (data not shown). Slightly higher dominant height at Col Piova was probably related  
151 to lower elevation.

152

153 Fig.1.

154

## 155 **2.2. Field methods**

156 Sampling points were located on a 100x100 m regular grid superimposed on each reserve. 33 points  
157 were identified within Val Novarza, 33 in Val Pontebbana, 36 in Col Piova, and 22 in Ludrin Forest  
158 Reserve (Figure 1). Field data were collected between 2005 and 2007. In correspondence of each  
159 sampling point, three type of measurement were applied: (1) a circular sampling plot (12-m radius,  
160 at Val Novarza, Val Pontebbana, Col Piova,) or a squared plot (30-m side, at Ludrin) for live trees  
161 measurement, (2) two perpendicular rectangular plots (50 x 8 m) for the stumps and the snags, and  
162 (3) two perpendicular 50 m long transects for line intersect sampling (LIS) for the logs (Van  
163 Wagner, 1968).

164 Snags were defined as standing dead trees having diameter at breast height (dbh) > 7 cm and height  
165 > 1.3 m, and stumps were wood pieces with diameter at the top > 7 cm and height < 1.3 m. Logs  
166 were stems, pieces of stem or branches laying on the ground having at least 5 cm diameter and  
167 length > 1 m.

168 For all live trees and snags with dbh > 7 cm, dbh and height were measured. The number of stumps  
169 was recorded. The measurement of logs consisted of the diameter at each intersection point (LIS

170 method). The decay stage of logs and snags was classified according to a class system from 1  
171 (slightly decayed) to 5 (very decayed) (see Motta et al. 2006 for decay class description).

172

### 173 **2.3. Stand and CWD descriptors**

174 Several stand characteristics describing forest structure, human disturbance, and topography have  
175 been considered as possible factors (explanatory variables) influencing CWD quantity and quality  
176 (focus variables).

177 In each sampling plot, the following forest structure descriptors were calculated: tree density ( $n \cdot \text{ha}^{-1}$ )  
178 <sup>1</sup>), basal area (BA) ( $\text{m}^2 \cdot \text{ha}^{-1}$ ), mean diameter at breast height (dbh) (cm), Shannon's diversity index  
179 for tree height (THD), proportion of trees having a BA bigger than the mean BA tree (%), BA  
180 proportions of the three principal species (%) (Drobyshev et al., 2008; Smirnova et al., 2008).

181 Human disturbance was evaluated through number of stumps ( $n \cdot \text{ha}^{-1}$ ) (all stumps were considered  
182 anthropogenic) and the time elapsed since last intervention derived from forest management plan  
183 archives (years). Topography descriptors were percent slope (%) and elevation (m a.s.l.) derived  
184 from a digital elevation model (10-m resolution) using ArcGIS 8.2 (ESRI Inc.).

185 Deadwood constituted by snags and logs was referred as coarse woody debris (CWD). Stumps were  
186 not included in CWD, since they were considered as indicators of human impact (Rouvinen et al.,  
187 2002). The volume ( $\text{m}^3 \cdot \text{ha}^{-1}$ ) of logs of each decay class and total was calculated using Van  
188 Wagner's formula (1968). The volume of standing dead trees (in classes and total) was estimated  
189 from yield tables, while the volume of the broken snags was estimated as a frustum of a cone  
190 (Motta et al., 2006). CWD was computed as logs and snags volume (CWD Tot), logs volume, snags  
191 volume, 1 and 2 CWD decay classes volume (CWD 1), 3, 4, and 5 CWD decay classes volume  
192 (CWD 2). To evaluate the occurrence of recently formed CWD in proportion to the total CWD  
193 volume, we calculated CWD ratio as the percent ratio between CWD 1 and CWD Tot.

194

### 195 **2.4. Statistical analyses**

196 Relationships between forest structure, human disturbance, topography and CWD were investigated  
197 adopting a multivariate approach. Redundancy analysis (RDA) was employed to explore  
198 relationships among all stand descriptors (explanatory variables) and CWD descriptors (focus  
199 variables) (Wimberly and Spies, 2001). Principal component analysis (PCA) was used to  
200 summarize CWD variability in few uncorrelated variables. Afterwards, a path analysis was  
201 employed to investigate the cause-and-effect relationships between CWD (expressed as PCs) and  
202 the most important explanatory variables (Shipley, 2000; Brais et al., 2005).



203 Prior to multivariate analyses, normality distribution of parameters was assessed and outlier  
204 analysis was performed using PcOrd 5 statistical package (McCune and Mefford, 1999). Each  
205 dataset was relativized by the standard deviate in order to put variables, that were measured in  
206 different units, on an equal footing (McCune and Grace, 2002).

207 All explanatory and focus variables calculated for each plot were included in the RDA matrix. This  
208 direct gradient analysis was performed using Canoco (Ter-Braak and Šmilauer, 1998) and the  
209 statistical significance of the relation between CWD and the explanatory variables was tested by a  
210 Monte Carlo test (9999 permutations).

211 A data matrix including six focus variables was processed to summarize CWD variability in fewer  
212 uncorrelated variables. PCA was performed using PcOrd 5 statistical package (McCune and  
213 Mefford, 1999) and statistical significance of the axes was tested by a Monte Carlo test (9999  
214 permutations). Moreover, Pearson's correlation between explanatory variables and the principal  
215 components (PCs) was calculated to find out explanatory variables more related to CWD  
216 variability. Variables with Pearson's  $r$  over 0.15 (absolute value) were selected.

217 A path analysis, which is a specialized version of Structural Equation Models (Shipley, 2000), was  
218 employed to develop a model describing the influence of explanatory variables on quantity and  
219 quality of deadwood (expressed as PCs). A conceptual path model including variables selected by  
220 Pearson's correlation analysis was built under the underlying concept that different stand  
221 characteristics interact together to determine CWD in the reserves (Fig. 2). Afterwards, alternative  
222 models were tested considering a subset of variables to obtain a statistically significant model  
223 (Garbarino et al., 2009). Quantitative model comparisons used a combination of Akaike's  
224 Information Criterion (AIC) statistic and the Root Mean Square Error of Approximation (RMSEA).  
225 The latter is a goodness-of-fit index that is relatively independent of sample size. A model with  
226  $RMSEA < 0.06$  was considered a good fit (Hu and Bentler, 1999). All such models were tested and  
227 the models with the smallest AIC statistic were selected as the most parsimonious models (Hu and  
228 Bentler, 1999). Path analyses were conducted using Mx software that works with covariance  
229 matrices as input data and a maximum likelihood (ML) fit function (Neale, 1994).

230

231 Fig. 2.

232

### 233 **3. Results**

#### 234 **3.1. Amount of CWD in the reserves**

235 Live tree volume was greatest at Val Novarza Reserve ( $594.9 \text{ m}^3 \text{ ha}^{-1}$ ), while CWD volume was  
236 greatest at Ludrin ( $68.4 \text{ m}^3 \text{ ha}^{-1}$ ). Col Piova showed the lowest values both for live and dead trees

237 (Table 1). However, values varied considerably among sample plots into the reserves, and the  
238 coefficient of variation ranged from 70% (Val Pontebbana) to 120% (Col Piova). A total absence of  
239 CWD was observed on one plot in Ludrin, and two plots in Col Piova. Based on outlier analysis,  
240 two plots involved in an uprooting episode in Val Novarza (CWD volume: 787 and 330 m<sup>3</sup> ha<sup>-1</sup>)  
241 were excluded from analyses. Considering all reserves as a whole, volume contribution of snags and  
242 logs to CWD was similar (46.5 and 53.5% respectively), but snags prevailed (59.1%) at Ludrin and  
243 logs prevailed (75.0%) at Col Piova.

244

245 Table 1

246 Stand characteristics and CWD volume in the Forest Reserves.

247

### 248 **3.2. Multivariate analyses of CWD and its anthropogenic and environmental relationships**

249 RDA was used to relate deadwood data to anthropogenic and environmental data. Monte Carlo  
250 permutations (n = 9999) indicated relations between variables being statistically significant (p =  
251 0.01). The first RDA axis explained 11.7 % of variance in CWD data, and the CWD-environment  
252 correlation for the first axis was 0.452. CWD Tot, CWD 1 and CWD 2 emerged to be correlated to  
253 each other, and were positively associated to stand density, elevation and basal area (Fig. 3).

254 Volume of snags was highly related to density, while logs volume was related to slope. The number  
255 of stumps and management variables, both indicators of anthropogenic disturbance, were correlated  
256 to each other, and were negatively related to total volume of CWD, density, BA and elevation.

257 Species BA proportions were not related to CWD variables. Beech proportion was higher at low  
258 elevation, and spruce at higher elevation. CWD ratio, a qualitative variable, seemed to be  
259 uncorrelated to other parameters.

260 PCA reduced CWD measures into uncorrelated components that explained most of the variation in  
261 the original dataset. The first two principal components explained 87.2% of the variation. PC 1  
262 extracted 59.4% of the variation in the dataset, and was significantly associated with quantitative  
263 CWD variables, particularly with CWD Tot (Table 2). PC 2 extracted a lower percentage of  
264 variation (27.7%), and it was associated with the qualitative CWD variable, i.e. CWD ratio. Both  
265 axes were highly significant (p = 0.0001, Monte Carlo test). BA, density, THD, and elevation were  
266 negatively correlated with the first component (PC 1) (Table 3). Management, proportion of beech  
267 and number of stumps were negatively correlated to PC 1. Weak correlations (r < 0.15) with the  
268 second principal component (PC 2) were found.

269

270 Fig. 3.

271 Table 2  
272 Principal component loadings for the first five axes for the four reserves.

273  
274 Table 3  
275 Pearson's correlation coefficients of the explanatory variables with the first 2 ordination axes  
276 (principal components).

277

### 278 **3.3. Causal model for CWD**

279 The conceptual model was used to derive alternative path diagrams for two synthetic descriptors of  
280 deadwood derived from the PCAs: CWD quantity (PC 1) and quality (PC 2). Seven explanatory  
281 variables on 12 were included in the first path model (Fig. 2). Since PC 2 explained a lower  
282 percentage of variation compared to PC 1, and no variables had  $r$  value over 0.15 with it, we did not  
283 perform a model to predict PC 2. A model emerged as having significant support (RMSEA < 0.001;  
284 AIC = -1.755) and included a topographic (elevation), a forest structure (basal area) and a human  
285 disturbance (management) variable (Fig. 4). CWD was positively influenced ( $\beta = 0.22$ ) by basal  
286 area of live trees, but was negatively ( $\beta = -0.20$ ) associated with management. The model included  
287 the interaction of topographic and anthropogenic influences in that the negative effect ( $\beta = -0.58$ ) of  
288 elevation on human disturbance (management) was explicitly represented. Moreover elevation was  
289 positively ( $\beta = 0.31$ ) associated with basal area.

290

291 Fig. 4.

292

## 293 **4. Discussion**

### 294 **4.1. Disturbance regime and amount of CWD in the reserves**

295 Connections between disturbance history and forest structure are critical for understanding  
296 ecological processes in the forest ecosystem (Bellemare et al., 2002; Foster et al., 2003; Gimmi et  
297 al., 2008; Fraver et al., 2009). The quantity and quality of deadwood can provide information on  
298 mortality processes and disturbance regime. Moreover, they can suggest the degree of forest  
299 naturalness, and indicate the proximity to the old-growth stage (Stokland, 2001; Woodall and  
300 Nagel, 2006; Winter et al., 2010).

301 In mixed temperate southern European forests, the natural disturbance regime mostly results in  
302 individual-tree death or small-scale disturbances caused by wind, insects, and fungi, while large-  
303 scale disturbances occur seldom (Nagel and Diaci, 2006; Firm et al., 2009; Kenderes et al., 2009).

304 In the studied reserves, only 2 out of 124 plots had high amounts of deadwood, reflecting the

305 absence of recent catastrophic disturbances. Distribution of deadwood in the reserves was related to  
306 single-tree mortality and small-scale wind disturbances.

307 In the eastern Italian Alps many forests have been left unmanaged in last decades due to social and  
308 economical changes. Their dynamics are presently influenced by autogenic and allogenic  
309 disturbances, but the current structure results from land use management history. Montane mixed  
310 forests analysed herein have been recently (from 12 to 50 years ago) withdrawn from regular  
311 management, thus an effect of former management on deadwood accumulation was expected.  
312 The total CWD volume found in study reserves was comparable or slightly lower than other  
313 recently-unmanaged mixed forests in central Europe (Bretz Guby and Dobbertin, 1996;  
314 Vandekerkhove et al., 2009). However montane mixed Fagus-Abies-Picea old-growth forests have  
315 much more CWD, generally over  $200 \text{ m}^3 \text{ ha}^{-1}$  (Vrška et al., 2001; Christensen et al., 2005; Motta et  
316 al., 2008). Our results suggest cessation of management for even 50 years is insufficient for  
317 accumulation of CWD comparable to old-growth forests.

318

#### 319 **4.2. Relationships between human disturbance, topography characteristics, forest structure** 320 **and CWD components**

321 Deadwood accumulation is influenced by a number of factors, resulting in a complex correlation  
322 structure between the involved variables. Thus, few studies have analyzed how different stand  
323 characteristics influence deadwood in a forest stand (Hély et al., 2000; Storaunet et al., 2000).  
324 In the forests analysed herein, the number of stumps and time of non-intervention were strictly  
325 related to each other. In case of a lack of historical information, the number of anthropogenic  
326 stumps can be used as a proxy variable of human impact (Storaunet et al., 2005). The number of  
327 stumps indicates the intensity of cutting (Siitonen et al., 2000) while historical archives can  
328 precisely point out the time span of non-intervention.

329 Elevation was more important than slope percentage in shaping the forest structure and CWD  
330 characteristics. At higher elevation, spruce stands had a higher density of live and dead trees.  
331 Recently-disturbed stands located at lower elevations had lower BA and CWD volume and were  
332 dominated by beech trees.

333 Ordination analyses (RDA) indicated a relationship between forest structure and CWD, since BA  
334 and tree density were positively correlated with CWD quantity. This relationship probably reveals  
335 the effect of density-dependent mortality. Besides, past logging activities influenced actual forest  
336 structure, as BA was negatively related to management and stump density. A few studies have  
337 shown tree species composition influence deadwood characteristics (Brassard and Chen, 2008).  
338 Nevertheless, type or decay class distribution of CWD in the reserves was not strongly affected by

339 species composition, although beech proportion was slightly negative related with CWD volume,  
340 possibly due to the rapid decomposition rate of its wood (von Oheimb et al., 2007). However, beech  
341 proportion was higher at low elevation, where generally smaller CWD amounts occurred, and a  
342 direct effect of beech proportion on CWD accumulation can not be ascertain.

343 Decay class distribution showed no pattern, as plots with higher quantity of low-decayed CWD had  
344 high quantity of high-decayed CWD as well. Moreover, the proportion of recently formed CWD  
345 (CWD ratio) was poorly correlated with other variables. Bretz Guby and Dobbertin (1996) found  
346 managed stands had more deadwood in higher decay stages than unmanaged stands in Switzerland.  
347 Burrascano et al. (2008) and Lombardi et al. (2008) found an opposite pattern in Central Italy.  
348 Inconsistency can be due to differences in species composition, disturbance type and decay  
349 processes (Yan et al., 2007). In contrast, the occurrence of logs and snags depended on plot  
350 characteristics. Snags were more abundant in stands having higher tree density, probably due to  
351 density-dependent mortality (Hély et al., 2000), while logs were more abundant in steep slope  
352 stands, where probability of uprooting is generally higher. Excluding anthropogenic stumps, effects  
353 of human disturbance on the type of CWD were not observed.

354

#### 355 **4.3. Effects of past forest management on forest structure and CWD accumulation**

356 Clarify causal relationships that determine the accumulation of deadwood in forest ecosystems is  
357 critical for forest ecology and ecosystem management. Consistent with the majority of previous  
358 studies (e.g. Christensen et al., 2005), the path model indicated that CWD was related to the time  
359 elapsed from human intervention, and to the amount (basal area) of live trees.

360 The CWD accumulation reflects the cumulative balance between inputs through tree mortality and  
361 outputs through decomposition and harvesting (Harmon et al., 1986; Tinker and Knight, 2000). In  
362 the studied plots mortality was mainly due to competition or, less frequently, to individual  
363 uprooting. Since competitive mortality depends on tree density, the input of CWD was connected  
364 with the basal area of live trees.

365 Past management affected CWD input in the reserves. Logging activities reduced stand basal area,  
366 affecting density-dependent mortality. Moreover, suppressed, unhealthy and senescent trees with a  
367 high potential for death, representing potential sources of CWD, were generally removed. Besides,  
368 past management influenced directly the output, as CWD was generally removed during harvesting  
369 activities.

370 Consistent with the results of Christiansen et al. (2005) we found higher CWD quantities at higher  
371 elevation. This trend was probably related to the negative elevation effect on management intensity.  
372 Human impact on forest ecosystem is generally stronger at low elevation, due to proximity to

373 human settlement, accessibility and higher forest productivity (Garbarino et al., 2009). Stands at  
374 higher elevation had higher basal area and lower human impact, and consequently higher CWD  
375 volume.

376

#### 377 **4.4. Future perspectives**

378 The majority of studies on deadwood have been carried out on natural forests influenced by  
379 catastrophic disturbances (Harmon, 2009). However, in southern European montane forests,  
380 individual, small-scale or, more rarely, intermediate disturbances, are dominant processes driving  
381 forest dynamics (Leibundgut, 1987; Kenderes et al., 2009). Besides, past and present presence of  
382 man affects all southern European forests (Winter et al., 2010). In mixed montane forests analysed  
383 herein, past forest management and stand density seem to be the major aspects influencing CWD  
384 accumulation. In the absence of further human interventions, we believe that in the next few  
385 decades increasing density-dependent mortality and small disturbances will result a CWD  
386 accumulation. However many decades will be required for accumulations of CWD comparable to  
387 those in old-growth forests.

388 Quantifying deadwood dynamics is critical for modeling and managing forest ecosystems for the  
389 development of old-growth conditions in southern Europe. Future studies of interactions between  
390 environmental factors, human disturbance and deadwood are required, especially for those forests,  
391 which have been withdrawn from regular management for long periods (e.g. 50-100 years). Such  
392 forests will be increasingly common in the next several decades.

393

394

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**Figure captions**

**Figure 1.** Location of the 124 sample plots in the four Forest Reserves in eastern Italian Alps.

**Figure 2.** Conceptual model tested through path analysis. The model includes forest structure (Basal Area, Density, Beech proportion, THD, vertical diversity), topographic (Elevation), and anthropogenic (Management, Stumps) variables. CWD refers to the first principal component (PC 1) defined as deadwood quantity.

**Figure 3.** Redundancy analysis ordination biplot of 122 plots in the reserves. Dotted arrows represent the biplot scores of deadwood variables (CWD Tot = total CWD volume; Logs = logs volume; Snags = snags volume; CWD1 = volume of the 1<sup>st</sup> and 2<sup>nd</sup> CWD decay classes; CWD2 = volume of 3<sup>rd</sup>, 4<sup>th</sup> and 5<sup>th</sup> CWD decay classes; CWD ratio = CWD1 / CWD Tot). Full-line arrows represent the biplot scores of forest structure, human disturbance and topography variables (BA = basal area; Big Trees = BA proportion of trees larger than the mean BA tree; DBH = mean diameter at breast height; Density = number of live trees; THD = height diversity; Aa = fir basal area proportion; Fs = beech basal area proportion; Pa = spruce basal area proportion; Management = inverse of time of non-intervention; Stumps = number of stumps; Elevation = elevation a.s.l.; Slope = percentage slope).

**Figure 4.** Path diagram for the studied reserves. Continuous lines, positive paths; dotted lines, negative paths; single arrow lines, causal paths; double arrow lines, covariance paths. Thickness of causal path vectors corresponds to the strength of effect. Only significant path coefficients are presented next to each path.

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Reserve	Area (ha)	Plots (n)	Elevation (m a.s.l.)	Last cutting (year)	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	Vol live trees (m <sup>3</sup> ha <sup>-1</sup> )	Vol CWD (m <sup>3</sup> ha <sup>-1</sup> )	Vol log (m <sup>3</sup> ha <sup>-1</sup> )	Vol snag (m <sup>3</sup> ha <sup>-1</sup> )
Val Novarza *	37.0	31	1300-1570	1953	53.1 (17.3)	594.9 (250.3)	45.8 (41.1)	25.1 (28.0)	20.7 (25.3)
Val Pontebbana	37.6	33	1240-1630	1996	43.6 (11.2)	470.7 (130.3)	31.0 (21.7)	16.4 (18.1)	14.6 (16.8)
Col Piova	36.0	36	1020-1200	1989	35.4 (11.3)	435.3 (158.1)	22.6 (27.0)	16.9 (22.5)	5.7 (12.4)
Ludrin	26.5	22	1250-1350	1962	48.3 (12.8)	531.3 (166.0)	68.4 (57.8)	28.0 (32.8)	40.4 (32.3)
All reserves	137.1	122	1020-1630	-	44.4 (14.8)	510.7 (187.6)	39.0 (40.0)	20.9 (25.2)	18.1 (24.5)

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3 **Table 1**

4 Stand characteristics and CWD volume in the Forest Reserves.

5 Standard deviations are indicated in parentheses. Two plots were considered outliers and excluded  
6 from the Val Novarza dataset (\*).

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Axis	PC 1	PC 2	PC 3	PC 4	PC 5
% of variance	59.45	27.72	10.25	1.32	0.99
Logs	-0.43	0.08	<b>-0.72</b>	0.35	0.42
Snags	-0.43	-0.15	<b>0.68</b>	0.36	0.45
CWD Tot	<b>-0.52</b>	-0.02	0.00	0.20	<b>-0.70</b>
CWD 1	-0.35	<b>-0.56</b>	-0.10	<b>-0.70</b>	0.18
CWD 2	-0.48	0.31	0.08	-0.26	-0.21
CWD ratio	0.11	<b>-0.75</b>	-0.11	0.38	-0.24

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14 **Table 2**

15 Principal component loadings for the first five axes for the four reserves.

16 Loadings greater than 0.5 (in absolute value) are indicated in bold.

	PC 1	PC 2
Density	<b>0.25</b>	0.06
Basal Area (BA)	<b>0.32</b>	0.08
Mean Diameter (DBH)	-0.08	0.01
Spruce (Pa)	0.09	0.03
Beech (Fs)	<b>-0.19</b>	-0.12
Fir (Aa)	0.10	0.05
Height diversity (THD)	<b>0.18</b>	0.09
Big trees	-0.07	0.03
Management	<b>-0.33</b>	-0.11
Stumps	<b>-0.18</b>	-0.01
Elevation	<b>0.22</b>	0.04
Slope	0.12	-0.03

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19 **Table 3**

20 Pearson's correlation coefficients of the explanatory variables with the first 2 ordination axes  
 21 (principal components).

22 Pearson's  $r$  values greater than 0.15 (in absolute value) are indicated in bold.

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Figure1  
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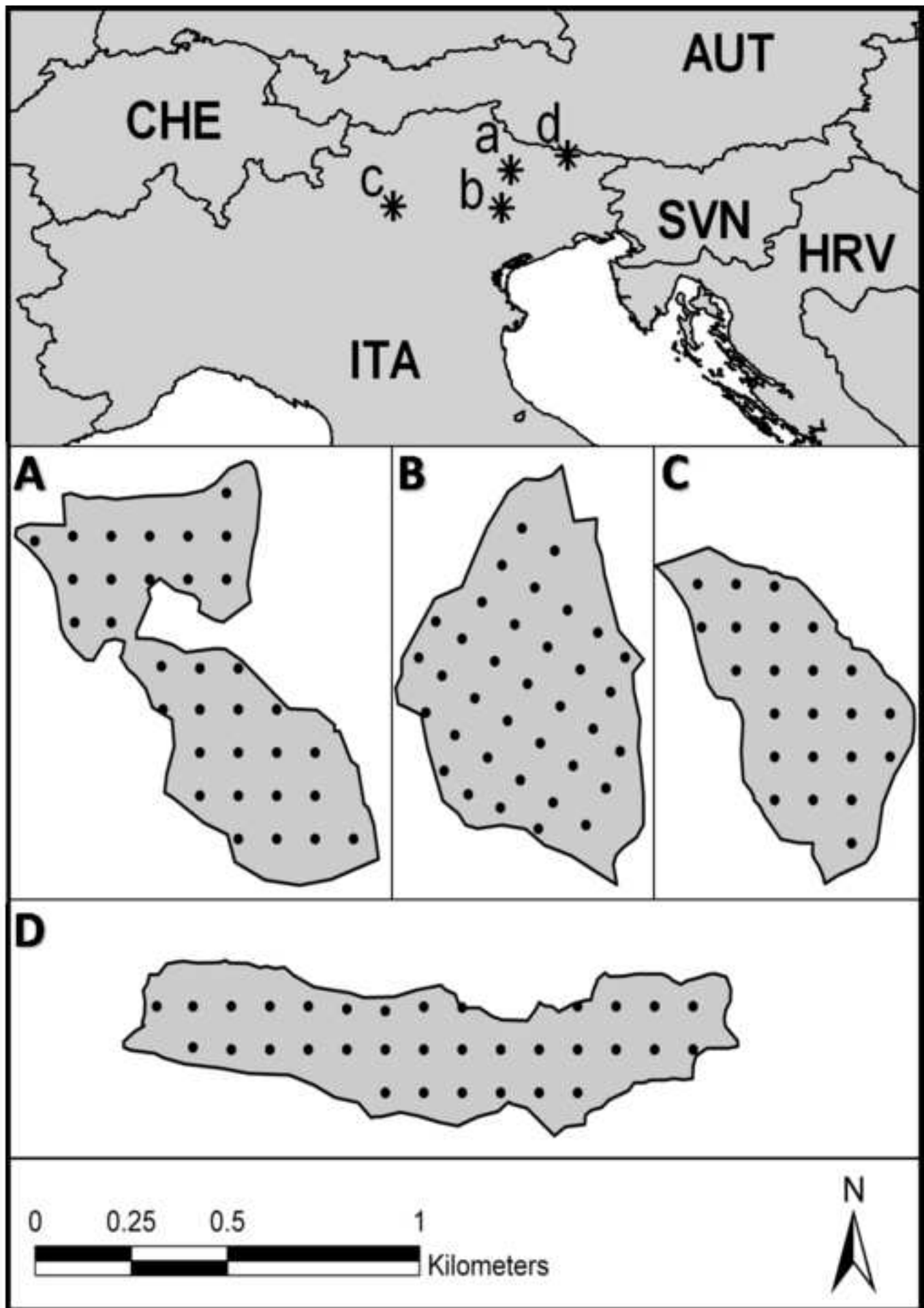


Figure2

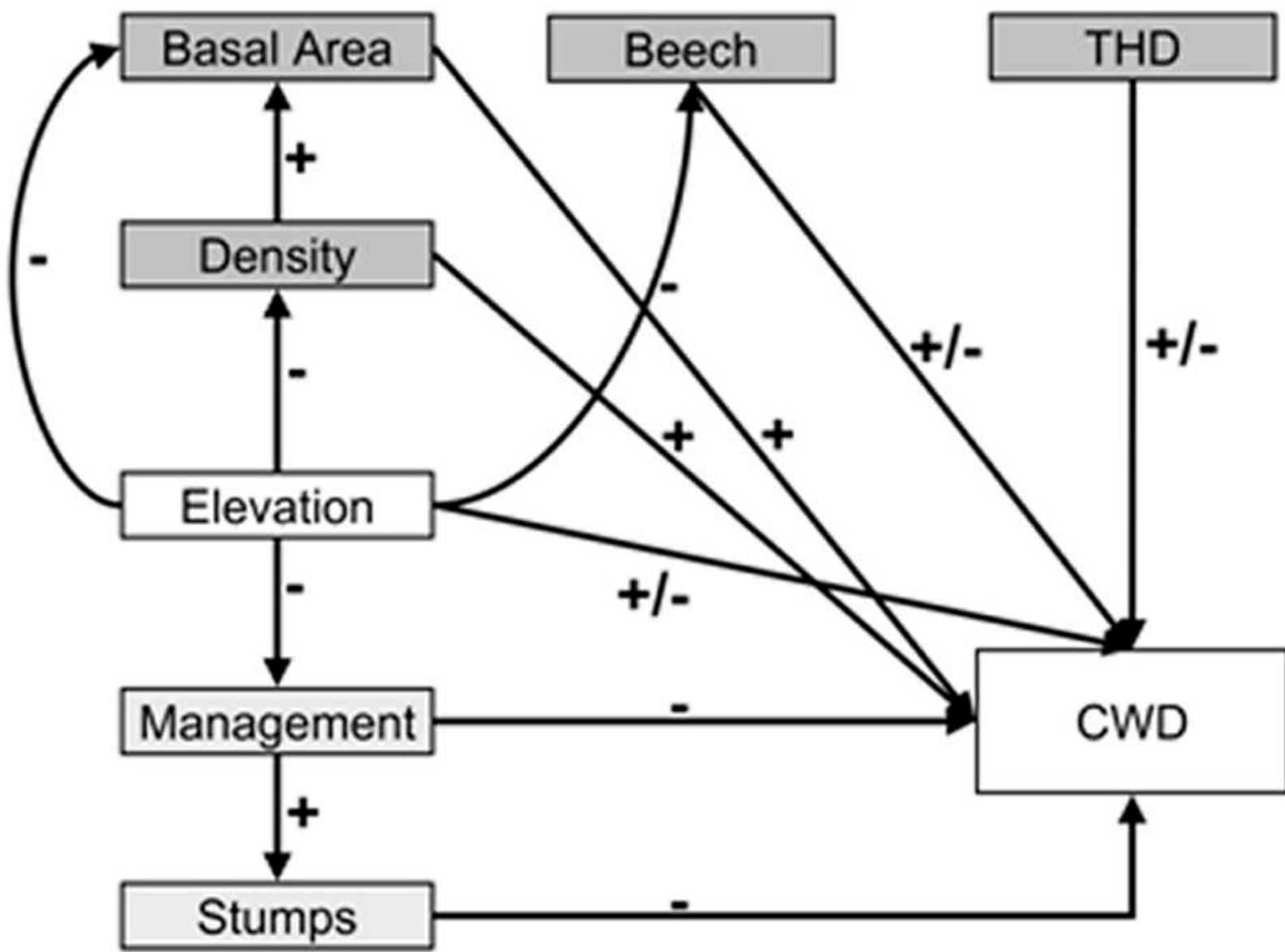




Figure3

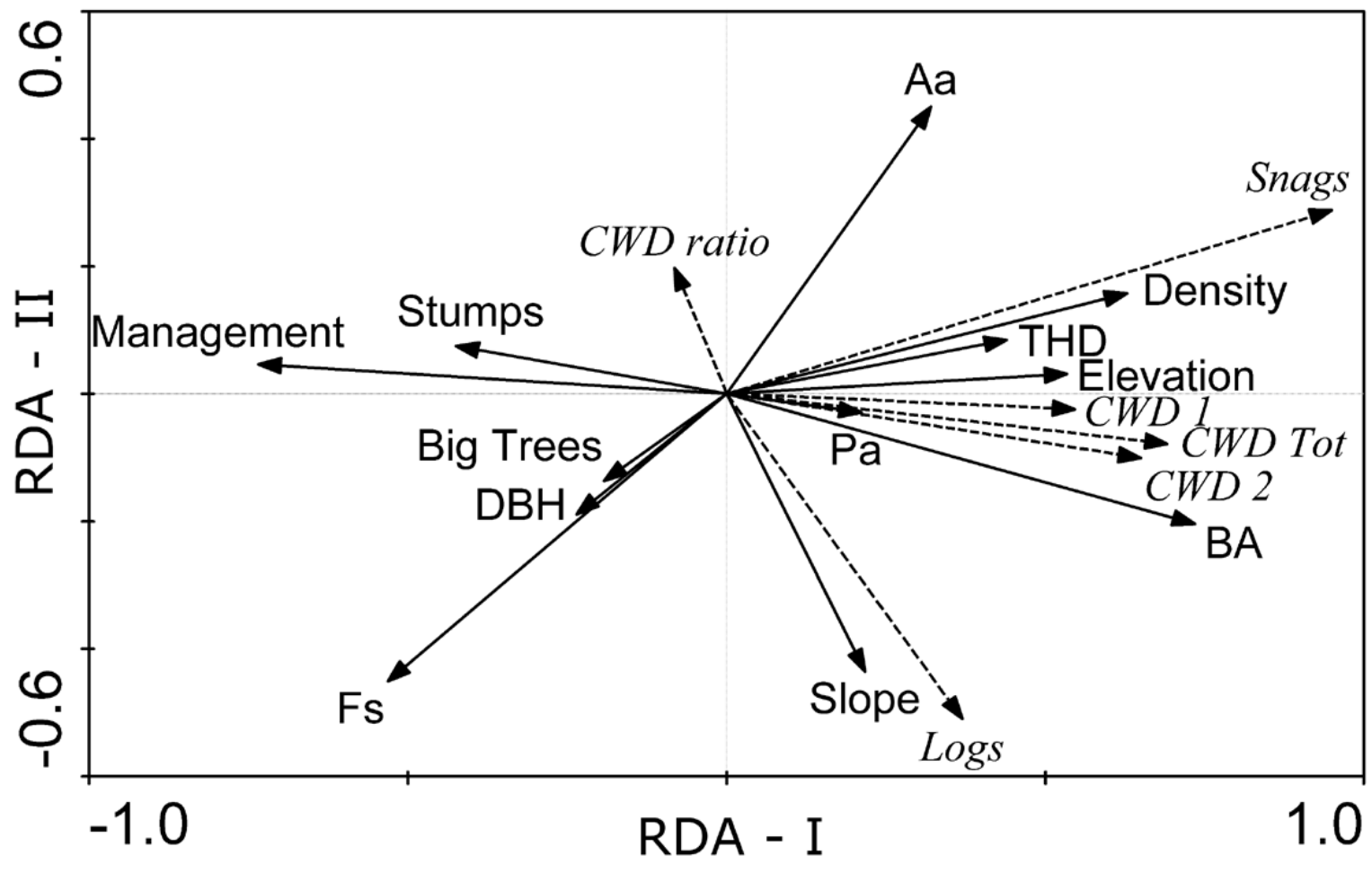


Figure4

