Spatial Structure in Four Norway Spruce Stands with Different Management History in the Alps and Carpathians

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In Europe most Norway spruce (*Picea abies* (L.) Karst.) mountain forests have been altered by human activities, leading to a lack of reference condition concerning their original structure. Nonetheless, remnants of Norway spruce primeval forests still exist in the Carpathians. Our objective was to assess the differences in structure between managed and unmanaged stands, concerning diameter distributions, amount of standing deadwood, spatial distributions and spatial structure of trees. We established four permanent plots: one in a virgin forest in the Eastern Carpathians and three in a previously managed forest in the Alps. In each plot, species, DBH, and position of the live and dead standing trees were collected. Spatial distribution and structure of all the trees was analysed through several indices. In the Carpathians forest there are clear signs of natural density-dependent mortality processes whereas in the Alpine plots such dynamics are less evident. In these latter plots, the lower snags volume and the random trees spatial distribution can be considered the legacies of past management. Nonetheless, despite the different history of the four stands, they all seem to converge towards a similar spatial structure with the presence of groups (30–40 m) of trees of similar size.

1 Introduction

Norway spruce (*Picea abies* (L.) Karst.) forests cover, although not evenly, large areas of Central Europe's mountainous region. These forests have a very long history of management, from timber production to the protection of civil infrastructure from avalanches and flooding (Kräuchi et al. 2000, Brang 2001, Spiecker 2003, Svoboda et al. 2010). For centuries if not millennia production has been the main function of Norway spruce forests and consequently in the temperate area, natural forests are now quite rare; many of the existing remnants are located in East European countries.

In the Italian Alps old-growth Norway spruce forests are entirely absent because of the past management based on timber production and grazing (Motta et al. 1999). However, since the second half of the 19th century, the socio-economic structure in most of the Italian Alps has dramatically changed, resulting in extensive land use changes and a significant reduction of human activities (Bätzing et al. 1996). As a consequence, many forests have been withdrawn from regular silvicultural management and have been growing without direct human influence (Vandekerkhove et al. 2009, Motta et al. 2010). If past human impact left no true old-growth stands, there are now many stands that have been evolving naturally for decades. Some of these forests are now part of reserves or natural parks, in order to preserve their natural development processes. The structure of such stands is the result of both natural processes, i.e. competition and disturbances, and past human-induced changes. Such a cultural legacy has important implications for the present-day structure and processes (Foster et al. 2003, Franklin et al. 2007, Motta et al. 2010), since the altered dynamics in natural stands may persist for the lifespan of the current tree population.

This paper examines the structure of four Norway spruce stands with different history: a virgin forest in the Carpathians and three stands in the Italian Alps characterised by different past management regimes. The purpose of the study was to assess the differences in structure between managed and unmanaged stands, concerning diameter distributions, amount of standing deadwood, spatial distributions and spatial structure of trees.

2 Material and Methods

2.1 Study Sites

We first selected two of the most representative forest reserve areas in order to better grasp the potential differences between pure spruce stands in the Carpathians and in the Alps. The Carpathian plot (GIU) is located in a 309.5 ha Norway spruce forest, the Codrul Secular Giumalau Forest Reserve (latitude 47°26'N, longitude 25°29'W) which was constituted in 1941 in the region of Suceava (Romania). It is situated in the Giumalau Mountains (Eastern Carpathians), in the basin of the Valea Putnei creek, affluent of the Moldova river. The Reserve is surrounded by a larger production forest. Altitudes range from 1200 to 1650 m a.s.l., the slope between 20° and 40° and the aspect is mainly N and W. The climate is cold temperate with mean annual temperature between 5.8 and 3.9°C and mean annual rainfall between 700 and 810 mm (three meteorological stations, 800–1100 m, 15 km away at maximum from the study site). The forest also includes rare *Sorbus aucuparia*, *Acer pseudoplatanus*, *Alnus incana* and *Betula pendula*. The substrate is composed of crystalline shale and limestone. The permanent plot was located at 1250 m a.s.l. within a typical old-growth stand with no record of current or past human disturbance.

The Alpine plots are located in the Valbona Forest Reserve (latitude 46°18'N, longitude 11°45'W), a 123 ha subalpine Norway spruce forest included in the Paneveggio-Pale di San Martino Natural Park (Trentino, Italy). Rainfall is around 1100 mm/year and annual mean temperature is around 3.7°C (Paneveggio meteorological station, 1508 m, 2 km from the study sites). The bedrock is porphyry and sandstone, and soils are podsols and rankers. The forest also includes rare *Larix decidua* and *Pinus cembra* in the upper area. The three plots are located along an altitudinal gradient: 1695 m a.s.l. (VB1), 1815 m (VB2) and 1865 m (VB3). The slope ranges between 17° and 25° and the aspect is NW-N for all sites. The three plots represent three different management situations: a) a stand managed for wood production until 1983 (VB1), b) a stand managed in the past, withdrawn from regular management about 60 years ago (VB2), c) a stand in an area

used in the past for forest grazing (VB3) (Motta et al. 1999).

2.2 Data Collection

Carpathian plot. In summer 2008 a 4-ha (200 x 200 m) permanent plot was established. All living and standing dead trees (diameter at breast height, DBH > 7.5 cm) were labelled with numbered tags and mapped (x, y coordinates). For each tree DBH and height were measured.

   Alpine plots. Three 1-ha (100 x 100 m) plots were established in 1993 and all living and standing dead trees with DBH > 7.5 cm were identified, labelled with numbered tags and mapped (x, y coordinates). For each living or dead tree DBH and height were measured. The inventory was repeated in 2005; the present study used the data coming from this latter dataset.

   The volume of live trees was calculated with local yield tables, while the volume of snag was calculated assimilating stems to the shape of a cone and broken stems to the shape of a cylinder.

2.3 Spatial Analysis

2.3.1 Ripley's K Function

We applied point pattern analysis techniques to describe the spatial patterns of trees within the plots. In order to test the spatial distribution, we used *Ripley's L(d)* function, (Ripley 1977). We applied univariate analysis to test the distribution in the whole stand and in the different DBH classes. In order to investigate if the trees were aggregated, regular or randomly distributed, we used the *complete spatial randomness* (CSR) null model, which can be implemented as a homogeneous Poisson process. Bivariate analysis was conducted to test how different DBH classes were distributed with respect to one another. The *antecedent conditions* null hypothesis was used in the bivariate analysis: we randomised only the smaller trees (DBH < 20 cm), keeping the bigger ones (DBH > 50 cm) position fixed. The bivariate function was also applied to test the *random mortality* hypothesis and spatial distribution of snags

with respect to live trees, using the *random labelling* null model. We performed the analysis up to 50 m distance and ran 999 simulations (p < 0.05). The analyses were conducted using the software Programita® (Wiegand and Moloney 2004).

2.3.2 Moran's I

In order to test if aggregated patterns were linked to the presence of groups of trees with different dimension, we performed spatial autocorrelation analysis to detect the possible presence of these groups. To obtain a global description of the plots, we used *Moran's I* index, a global index which computes the degree of correlation between the values of a variable (in our case, DBH) as a function of spatial lags (Fortin et al. 2002). The analyses were computed with a lag distance of 10 m, up to the maximum size of the plot. We considered values of $|z(d)| > 2.58$ (p < 0.01). The calculations of *Moran's I* were computed with the Excel add-in Rookcase (Sawada 1999).

2.3.3 Local Gi*

In order to obtain a spatial localization of the tree groups highlighted by the global autocorrelation index, we applied a local index of spatial association (LISA), which allows the contribution to be determined of each single event in the global trend of the distribution (Anselin 1995, Fortin et al. 2002). In particular, we used the *local Gi** statistic (Getis and Ord 1992, Getis and Ord 1996), which characterizes the spatial autocorrelation of attribute values located within a lag distance *d* of each locality (tree) of the distribution. In order to be consistent with the spatial distribution analysis, we used the average distance that emerged from *Ripley's K* function analysis as lag distance, which described the size of the groups in the plots, where present. The calculations were computed using the Excel add-in Rookcase (Sawada 1999). We considered values of $|z(d)| > 2.58$ (p > 0.01). The maps were created using the natural neighbour interpolation technique with the program Surfer® 8 (Keckler 1995).

Table 1. Characteristics of the four permanent plots.

|	GIU		VB1		VB2		VB3	
	Living trees	Snags	Living trees	Snags	Living trees	Snags	Living trees	Snags
N (trees ha^{-1})	348	106	476	10	510	101	533	31
Basal Area (m^{2}ha^{-1})	42.1	6.4	64.6	0.5	73.7	5.9	43.3	0.9
SMD (m^2)	39.2	28.1	41.6	24.0	42.9	27.2	32.2	19.7
DBH max (cm)	95.0	73.5	73.5	44.0	73.0	60.0	92.0	49.0
Mean Height (m)	26.6	12.4	29.4	16.8	28.0	13.1	11.9	4.1
Height max (m)	48.5	39.5	43.1	31.6	39.6	26.3	30.6	22.0
VOL (m^{3}ha^{-1})	492.2	41.7	946.0	3.4	977.0	32.0	368.6	3.3

Note: SMD = square mean diameter.
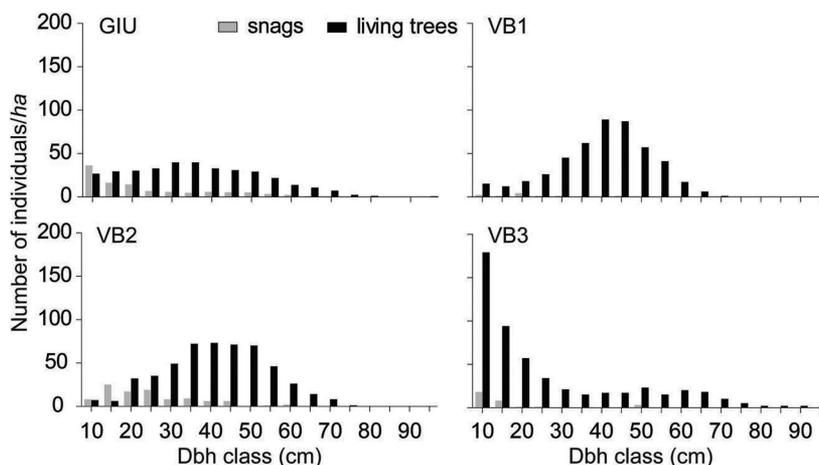
Fig. 1. Diameter distribution in the four permanent plots in the Carpathians (GIU) and in the Alps (VB1, VB2 and VB3).

3 Results

3.1 Stand Characteristics

Stand characteristics are summarised in Table 1. The Carpathians GIU stand presents the lowest values of tree density, basal area, mean DBH and mean height. On the other hand, it has the greatest DBH and height. The diameter distribution is quite homogeneous in lower to medium DBH classes (Fig. 1). The Alpine stands show different trends: VB1 and VB2 present an even-sized structure, with a unimodal diameter distribution (Motta et al. 2010) (Fig. 1). On the contrary, VB3 has an uneven-sized DBH distribution, due to the large number of smaller (< 20 cm) diameter classes. The virgin forest has the highest rate of dead trees per ha and the biggest snag/total basal

area. Among the three Alpine stands, only VB2 has quite a large number of snags and a comparable volume, although the dead/live trees ratio is still lower than in GIU.

3.2 Spatial Distribution

The Carpathians GIU stand shows significant clustering of trees at all distances (Fig. 2A). This spatial pattern is strongly influenced by the smaller DBH (< 20 cm) (Fig. 2B), which are clustered in very large groups. On the contrary, bigger trees (DBH > 50 cm) have a regular distribution from 3 to 5 m, and random spatial pattern up to 50 m. Snag distribution was found to be aggregated up to about 45 m, with a maximum at about 30 m (figure not shown). Bivariate *Ripley's* $L_{12}(d)$ func-
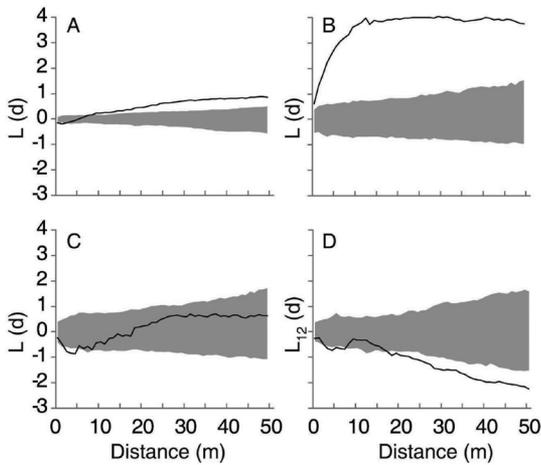
Fig. 2. Univariate *Ripley's L(d)* function in the GIU plot: A) all trees, B) trees with DBH < 20 cm, C) trees with DBH > 50 cm. Bivariate *Ripley's L₁₂(d)* function: D) trees with DBH < 20 cm *vs*. DBH > 50 cm. Shaded area represents the 95% confidence envelopes.

Fig. 3. Univariate *Ripley's L(d)* function for the overall tree population in the Alpine plots: A) VB1, B) VB2, C) VB3. Bivariate *Ripley's L₁₂(d)* function computed for trees with DBH < 20 cm *vs*. trees with DBH > 50 cm: D) VB1, E) VB2, F) VB3. Shaded area represents the 95% confidence envelopes.

tion shows a general trend of repulsion between smaller and bigger diameter classes (Fig. 2D), with significant values for most of the distances. Attraction was found up to 3 m between live and standing dead trees (figure not shown).

Concerning the Alpine stands, VB1 and VB2 present a random distribution (Fig. 3A and 3B) of all the trees, and the bivariate *Ripley's L₁₂(d)* function doesn't highlight any particular pattern between different size classes (Fig. 3D and 3E). We also analysed the distribution of the other diameter classes through univariate analysis, as for GIU stand: no significant values were found. In VB3 all the trees present an aggregated pattern at all distances, with a maximum at 25 m (Fig. 3C). This pattern is mostly affected by smaller DBH classes spatial distribution. Bivariate *Ripley's L₁₂(d)* function shows segregation up to 20 m between smaller and bigger diameter classes (Fig. 3F). In this plot, smaller DBH classes are significantly clustered, with higher values with respect to the whole stand. Both univariate and bivariate analyses on snag distribution, showing a random pattern in all the three plots, likely confirm no significant difference from the random mortality hypothesis (figure not shown).
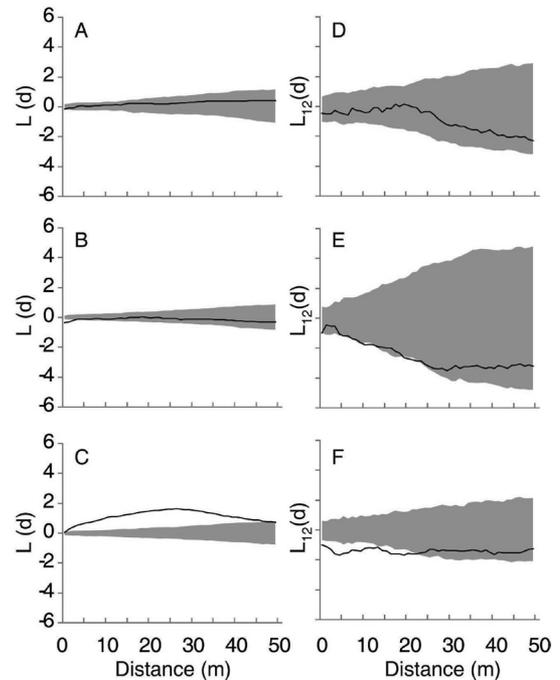
3.3 Spatial Structure

In the Carpathians GIU stand, *Moran's I* indices highlight the presence of a dimensional gradient, with two groups of trees with similar DBH, of about 60 m (Fig 4 above). *Local Gi** statistic allows these groups of trees with similar DBH to be identified and placed. Fig. 4 below shows where the groups of trees are in the plot: 3 areas can be distinguished where trees have DBH smaller than the average, with the largest group in the lower right part of the plot. There is then a large group of bigger trees that covers almost all the upper right quadrant of the plot. Spatial structure of snags analysed through *Moran's I* highlighted the same dimensional gradient (not shown). Concerning the Alpine plots (Fig. 5), VB1 does not show any particular pattern although *local Gi**
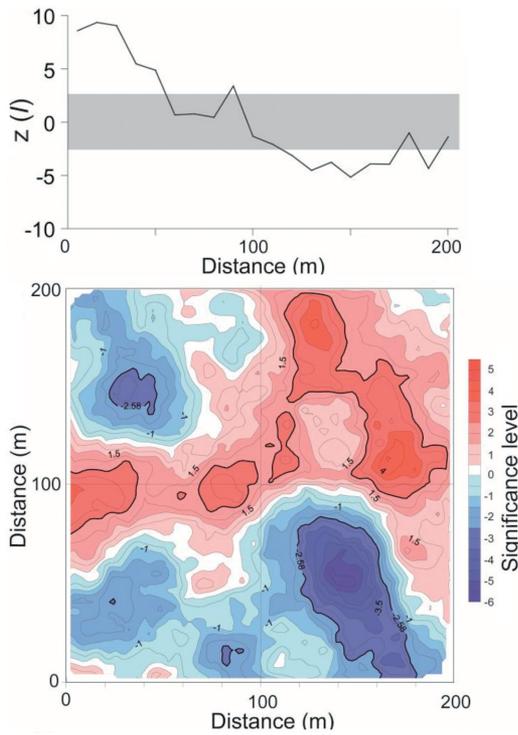
output points out two different zones with trees of different mean DBH that does not reach the significance threshold (Fig. 5A). VB2 presents a slightly significant DBH gradient with groups of about 30 m (Fig. 5B), VB3 shows the same trend, with a DBH gradient that separates groups of trees of about 30 m (Fig. 5C), here both *Moran's I* and *local Gi** have higher and significant values than in VB1 and VB2, and we can see from Fig. 5C that in VB3 the groups are larger than in the other two plots. So, regardless of the significance level,

Fig. 4. Global and local spatial autocorrelation in the GIU plot for tree size (DBH). Above, *Moran's I* correlogram; shaded area highlights not significant (P > 0.01) values. Below, map of the *local $G_i^*(d)$* computed for a distance of 20 m. Red represents hot spots (trees with DBH larger than the average), blue represents cold spots (trees with DBH smaller than the average). Bold contour lines comprise significant (P < 0.01) values.

Fig. 5. Global and local spatial autocorrelation in the Alpine stands. Above, *Moran's I* correlograms for A) VB1, B) VB2 and C) VB3. Shaded areas highlight not significant (P > 0.01) values. Below, the corresponding maps of the *local $G_i^*(d)$* computed for a distance of 20 m. Red represents hot spots (trees with DBH larger than the average), blue represents cold spots (trees with DBH smaller than the average). Bold contour lines comprise significant (P < 0.01) values.
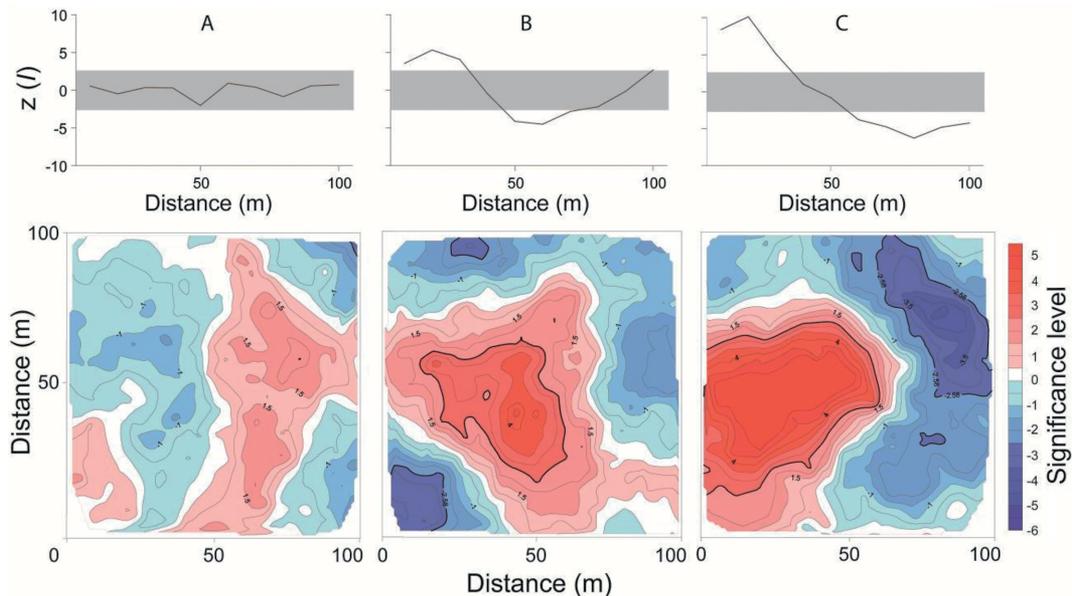
the plots show the same kind of spatial structure, with groups of individuals with similar DBH. This structure is much more evident in the less disturbed plots: the Carpathians GIU and Alpine VB3.

4 Discussion

Structurally, old-growth and primeval forests are characterised by a wide within-stand range of tree sizes and include trees that are large for the particular species and site combination (Franklin and Spies 1991, Frelich and Reich 2003) so, it is not surprising to find that the natural forest presents the biggest individuals (maximum DBH and height). On the other hand, VB1 and VB2 present a unimodal DBH distribution, with all the trees comprised within a smaller DBH and height range and with no individuals reaching considerable size. VB3 shows a different DBH distribution, similar to an uneven-aged stand. All three Alpine stands show signs of the past human activities due either to management aimed mainly at wood production (VB1 and VB2), or to the withdrawal of the wood pasture in an open Norway spruce stand with the subsequent establishment of a secondary population (VB3) (Motta et al. 1999). VB3 is located at higher altitude than VB1 and VB2, so the environmental conditions may also play a role in affecting its structure. Old-growth and virgin forests usually present a typical reverse J-shape DBH distribution (Kuuluvainen et al. 1998, Svensson and Jeglum 2001, Motta et al. 2010). We found that GIU is lacking the large amount of small classes typical of that structure and the DBH classes are quite evenly distributed. A similar distribution was found in an old-growth Norway spruce stand in the Bohemian Forest (Svoboda and Pouska 2008) and in a primeval Norway spruce forest in southern Finland (Kuuluvainen et al. 1996). This distribution is likely related to some medium-size disturbances, typical in these stands, which on the one hand have altered the uneven-sized structure of the forest and, on the other, call for a wider scale of analysis in order to fully catch the whole stand structure.

Natural mature and old-growth forests usually have large volumes of coarse woody debris in different stages of decay (Spies et al. 1988, Harmon et al. 2004). If we compare the snag volume in the Carpathians (GIU) with other old-growth and pristine Norway spruce forests, we observe that the value in GIU is lower than the average values observed in the temperate area (Kuuluvainen et al. 1998, Holeksa 2001, Svensson and Jeglum 2001, Zielonka 2006, Holeksa et al. 2007, Aakala et al. 2008, Svoboda and Pouska 2008). Nevertheless, the number and volume of snags are both higher in this natural stand than in the previously managed forests where natural mortality is only a recent phenomenon. Concerning the DBH distribution of standing dead trees, in GIU it is comparable to a reverse J shape. Mortality is affecting mainly trees of small and intermediate diameter (dominated or suppressed individuals) suggesting that current mortality processes are mainly due to competitive thinning, since competition for light is apparently a central factor limiting photosynthesis in *Picea* stands (Schulze et al. 1977, Kuuluvainen et al. 1998). However, mortality also affects larger and dominant trees, revealing the old growth status of the forest (Franklin et al. 1987). In the Alpine plots these dynamics are not yet visible because the time since the last commercial thinning is too short and the mortality dynamics are still affected by the past anthropogenic forest structure that altered competition dynamics.

As a result of the past forest management, VB1 and VB2 are homogeneous not only in the stand size structure, but also in their spatial organization. Conversely, GIU presents a spatial pattern that reflects natural dynamics affecting forest structure. In this context, wind could have an important role (Popa 2006): initial gaps would be caused by wind and then filled in by large clusters of regeneration; the self-thinning processes with density-dependent mortality would then thin out the clusters. The reduction of aggregation with tree growth has been observed in different forests (Getzin et al. 2008, Zhang et al. 2009, Szewczyk and Szwagrzyk 2010). Moreover, the snag distribution in GIU presents an aggregated trend, confirming the density-mortality hypothesis (Kenkel 1988). In the Alpine VB3 we observed a similar trend to that in GIU: clustered distribution mainly affected by smaller DBH classes and segregation between small and big size classes. This situation seems to take this stand closer to the picture of

a natural forest and probably relates to the past management as wood pasture. The current tree population established naturally within the former open woodland and did not suffer human disturbances. These dynamics are currently typical and widespread in the Alps (Carrer and Urbinati 2001, Garbarino et al. 2011).

Looking at the spatial structure it emerges that all the plots have large groups with different tree size. Although this pattern is much more evident in the natural forest than in the Alpine ones, we observed that the spatial structure tends to be rather similar with the previously managed stands recovering a more natural structure. These outcomes could represent an indication that pure Norway spruce stands likely converge towards the same spatial structure, despite a different stand history, DBH structure and environmental conditions. A close to nature management approach should take this spatial pattern tendency into account, avoiding both large clear-cuttings or single-tree logging. Yet, in order to refine and soundly base silvicultural practices, further studies in forests with different stand history are needed to confirm whether these findings could be generalized.

Acknowledgements

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