GIANLUCA PIOVESAN (*) (°) - ALFREDO ALESSANDRINI (*)
MICHELE BALIVA (*) (**) - TOMMASO CHITI (***)
ETTORE D'ANDREA (***) (****) - BRUNO DE CINTI (****)
ALFREDO DI FILIPPO (*) - LUIGI HERMANIN (*****)
MARCO LAUTERI (**) - GIUSEPPE SCARASCIA MUGNOZZA (******)
BARTOLOMEO SCHIRONE (*) - EMANUELE ZIACO (*)
GIORGIO MATTEUCCI (****) (*******)

STRUCTURAL PATTERNS, GROWTH PROCESSES, CARBON STOCKS IN AN ITALIAN NETWORK OF OLD-GROWTH BEECH FORESTS

In the framework of the Project of National Interest (PRIN) "Climate change and forests - Dendroecological and ecophysiological responses, productivity and carbon balance on the Italian network of old-growth beech forests", 9 old beech (Fagus sylvatica L.) *forests were sampled in the eastern Alps and in the central Apennines to assess: i) the degree of 'old-growthness' on a structural and dendroecological basis; ii) the carbon (C) stocks in the different ecosystem compartments; iii) some ecophysiological traits using stable isotopes.*

Live and dead tree structure, soil features and C stocks were examined in some among the oldest and less disturbed beech forests in Italy. Furthermore, leaves, litter and wood cores were sampled for concurrent dendroecological, nutrient and stable isotope analysis, to study age structure, disturbance history and medium- and long-term response to climate and ecophysiological traits.

In all sampled stands, values of basal area, volume and large trees density reached or exceeded control values reported for European and North American old-growth forests, while total amount of deadwood was generally low, except in two sites. Diameter distribution showed a remarkable differentiation from bimodal to 'rotated-sigmoid' curve. In accordance with structural analyses, disturbance chronologies revealed the importance of frequent low-to-moderate events in generating a fine-scale structure, confirming previous

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(*) DAF, University of Tuscia.
(**) Consiglio Nazionale delle Ricerca, Istituto di Biologia Agroambientale e Forestale (CNR-IBAF); Villa Paolina, Porano (TR).
(***) DISAFRI, University of Tuscia.
(****) Consiglio Nazionale delle Ricerche, Istituto di Biologia Agroambientale e Forestale (CNR-IBAF), Area della Ricerca Roma 1; Monterotondo Scalo (RM).
(*****) Università degli Studi di Firenze.
(******) Consiglio per la Ricerche e la Sperimentazione in Agricoltura, Dipartimento Agronomia, Foreste e Territorio (CRA-DAF); via del Caravita 7a, Roma (RM).
(*******) Consiglio Nazionale delle Ricerca, Istituto per i Sistemi Agricoli e Forestali del Mediterraneo (CNR-ISAFOM); Rende (CS).
(°) Corresponding author: piovesan@unitus.it

results on beech forests. Different degrees of 'old-growthness' were identified for Alpine and Apennine beech stands through the 'structural-based approach', which proved to be a valid tool for old-growth forests detection. Preliminary results on carbon stocks on a subset of sites indicate that these old-growth forests are relevant carbon reservoirs, with 192-268 MgC ha^{-1} of total biomass (67-73% aboveground; 27-33% belowground, 4 stands) and 7-21 MgC ha^{-1} of deadwood. In these stands, also forest floor (excluding deadwood) and soils are stores of relevant amount of carbon (5-9 MgC ha^{-1} litter layer, 4 stands; 168-420 MgC ha^{-1} mineral soil, 3 stands). Finally, carbon isotope discrimination (Δ) analysis, a proxy of water-use efficiency, was applied on tree-ring cores from a subset of sites. The perspectives of this technique for a retrospective ecophysiological interpretation of climate-change impact on old-growth forests were described.

Preliminary results obtained within this PRIN project indicate that the reported ecological indicators can be used to produce a description of forest structures and processes driving stand dynamics ('structural-based approach'). Furthermore, the use of multiple sampling and research techniques and the integration of research groups with complementary expertise can foster deeper understanding of the ecology and dynamics of old-growth forests.

Key words: old-growth forests; tree-ring; dendroecology; disturbance regime; carbon stocks; stable isotopes.
Parole chiave: foresta vetusta; dendroecologia; regime di disturbo; stock di carbonio; isotopi stabili.

1. INTRODUCTION

Studies on old-growth forests are continuously increasing: the database of SCOPUS (www.scopus.com) reports 2167 articles from 1975 to may 28th 2010, of which 81 were in 2010.

An old-growth forest is a forest ecosystem whose structural features are influenced by the presence of old trees (SPIES, 2004). However, describing old-growth forests by only considering the age of the oldest trees might appear too restrictive, since this approach could be overly linked to an anthropocentric vision of nature (FRELICH and REICH, 2003). Moreover, the oldest individuals often do not reach impressive diameters: reduced growth rates and dimensions, typical of the extreme sites where old-growth forests are often found, represent important factors contributing to tree longevity in marginal sites (PEÑUELAS, 2005). At the same time, forest structure alone is not sufficient to define the naturalness degree of a given stand. In this respect, bio-ecological processes typical of natural forests (i.e. the presence of large-sized senescent and dying trees and the disturbance regime which shape the canopy structure and dynamics) should be characterized (NAGEL et al., 2007).

From this point of view an old-growth structure in temperate deciduous forests can be recognized when dominant old trees start experiencing mortality after natural events (e.g. windthrows, glaze storms, droughts) and new space (canopy gaps) for the establishment of new cohorts

is created (DI FILIPPO *et al.*, 2005). Old-growth forests can further be distinguished as *primary* or *secondary* (FRELICH and REICH, 2003). In primary old-growth stands there isn't evidence of anthropogenic disturbances, not even in dendroecological series, while secondary old-growth forests structures and dynamics have been influenced by human activities in the more or less recent past.

Old-growth forests are important for biodiversity conservation and as carbon reservoirs. Research on their contribution to the global carbon cycle are increasing (LUYSSAERT *et al.*, 2008; WIRTH *et al.*, 2009), even though the application of techniques used in managed forests could underestimate their role as carbon sinks (CAREY *et al.*, 2001). Recent studies highlighted that, contrary to the traditional view on their carbon neutrality, old-growth forests can continue to accumulate carbon (LUYSSAERT *et al.*, 2008), even in their soils (ZHOU *et al.*, 2006).

Hence, old-growth beech forests could provide crucial informations about structural dynamics, growth and carbon stocks in conditions of reduced human impacts. In particular, within the context of climate change impact on forests, a main concern deals with changes in frequency and extent of drought, particularly in the Mediterranean area. These occurrences are likely to determine hard selective pressures on forest stands. If not equipped with enough resilience to new conditions, many forest populations could disappear, especially across the southern distribution areas. In this context, it must be considered that the number of studies dealing with old-growth stands in the Mediterranean area is still very limited (JUMP *et al.*, 2006).

Recent studies focused on the physiological character "water-use efficiency" (WUE) to describe forest species adaptiveness to drought conditions (GUEHL *et al.*, 1995; LAUTERI *et al.*, 2004). The physiological significance of WUE is addressed in the plant carbon - water economy, represented by the ratio between plant carbon gain and water losses. From an ecophysiological perspective, WUE is related to the balance between ecosystem net carbon fluxes and water losses through transpiration and evaporation. To our knowledge, nothing is known about WUE of old-growth beech forests. Carbon stable isotope analysis is at present the most reliable and the least intrusive methodology to study WUE in natural environments (LAUTERI *et al.*, 1997; BRUGNOLI and FARQUHAR, 2000). The heavy stable isotope ^{13}C is discriminated during the photosynthetic CO_2 assimilation (FARQUHAR *et al.*, 1989). As a consequence, plant carbon is invariably lighter than atmospheric C: the so-called carbon isotope discrimination (Δ). Δ is regulated by many physiological, genetic, silvicultural or environmental factors also influencing WUE (FARQUHAR *et al.*, 1982; LAUTERI *et al.*, 2004). Carbon isotope discrimination in tree rings (MCCARROL AND LOADER, 2004)

allows for the study of fluctuations in WUE on a long time scale (from seasons to centuries).

Dendroecology is an effective tool to investigate past forest dynamics (e.g. PIOVESAN *et al.*, 2005b), and in assessing the climate variability impact on tree-growth (e.g. PIOVESAN *et al.*, 2005a; DI FILIPPO *et al.*, 2007) and stand productivity (e.g. PIOVESAN *et al.*, 2008) at different geographic locations, while the detailed assessment of carbon stocks in the different ecosystem compartments (live and dead biomass, roots, litter, soil) can elucidate carbon allocation patterns and will provide data on overall carbon cycling. Thus, in the predicted climatic change, a comprehensive approach using dendroecological, ecological and ecophysiological techniques will provide important data and information on old-growth forests functioning and, in the end, will help to choose the proper management options for nature conservation and mitigation strategies.

In Italy, old-growth beech forests are rare biocenoses present across the Apennines and the Alps. Because of their occurrence along such a wide latitudinal gradient (climate, site, nitrogen deposition), these forests constitute an interesting study case in the topic of forest acclimation and adaptation to global changes. This paper reports the preliminary results of an Italian Research Project (PRIN) about the ecology, structure, auxology, carbon stocks and ecophysiology of primary and secondary montane and high-montane old-growth beech forests of the eastern Alps and central Italy.

2. MATERIALS AND METHODS

2.1. *Study sites*

A total of 9 Italian beech (*Fagus sylvatica* L.) old-growth forests were sampled for this study.

In the Alpine Region we selected 5 old-growth stands situated in the Carnic Alps (Friuli-Venezia Giulia region, Udine province), where beech was the dominant species. Elevation ranges from 825 to 1450 m a.s.l. (Table 1). With reference to the study areas, Carnic Alps pertain to temperate climate, according to the KÖPPEN-TREWARTHA classification (TREWARTHA, 1968). Almost all stands were situated above small towns where topography is generally strongly sloping (in most cases 70-100%): for this reason they have been historically protected from logging to be maintained as "protection forests" ("boschi banditi"; DI FILIPPO *et al.*, 2007) and have been publicly owned since the 16th century, when they were managed by the Republic of Venice (PAIERO *et al.*, 1975).

Table 1 – Geographical features of the sampled forests.

Site	Code	Latitude (°)	Longitude (°)	Elevation (m a.s.l.)	Slope (%)	Aspect	Stand area* (ha)	Inventory method	Sampled area* (ha)	Number of plots
Alpine stands										
Lateis	LAT	46.4594	12.7489	1450 (1370-1530)	75-110	S	20	Circular plots	0.72	6
Trelli	TRL	46.4997	13.0978	950 (850-1050)	60-70	SE	7	Circular plots	0.34	5
Timau	TIM	46.5817	13.0050	1160 (825-1500)	70-90	S	20	Circular plots	0.29	7
Gracco	GRA	46.5514	12.8519	825 (750-900)	70-90	S	6	Total stand inventory	6.00	–
Cleulis	CLE	46.5584	13.0006	930	20-60	NE	14	Total stand inventory	14.00	–
Apennine stands										
Val Cervara	VCH	41.8690	13.6230	1725 (1600-1850)	40-65	W	24	Circular plots+Transects	2.20	18 + 2
Coppo del Principe	COP	41.7883	13.7381	1625 (1500-1750)	20-60	NE	45	Circular plots	0.84	7
Fonte Regna	REG	42.3247	12.7194	954 (880-1010)	50-60	W	5	Transect	0.47	1
Monte Cimino	CIM	42.4181	12.2350	1000 (950-1050)	0-35	W	62	Circular plots	3.00	25

* Areas corrected for slope.

In central Italy, 4 old-growth beech forests were sampled. In the landscape of peninsular Italy, old-growth primary forest remnants can only be found at high elevation (PIOVESAN *et al.*, 2005b), while it could result easier to find secondary old-growth forests whose protection has been linked to their aesthetic-socio-cultural value (Monte Cimino, CIM; Fonte Regna, REG). The old-growth forests of Valle Cervara (VCH) and Coppo del Principe (COP) are located inside the Abruzzo-Lazio-Molise National Park (PNALM; Abruzzi region, L'Aquila province). The climate regime can be described as Mediterranean montane, with cold snowy winters and dry summers (PIOVESAN *et al.*, 2003); both stands are high-elevation beech forests which escaped logging because of their difficult access and probably even because of their protective function against avalanches and landslides (PIOVESAN *et al.*, 2005b). VCH (for acronyms see Table 1) beech forest is a primary multicohort forest (FRELICH, 2002), with an uneven-aged structure that includes the oldest known *Fagus* tree (more that 500 years old; tree cored by L. HERMANIN) in the Northern Hemisphere (PIOVESAN *et al.*, 2005b). COP, located close to VCH, is a forest showing several senescent and/or dying individuals. CIM and REG are secondary old-growth mountain forests situated in the Latium region (Viterbo and Rieti province, respectively). The beech stand of Monte Cimino is at the top of the homonymous mountain; it was managed for a long time as a low-density grazing forest, but during the 19th century, under the pressure of local communities, the social-aesthetic value of the site became prominent so that timber logging ceased in 1949 (LO MONACO, 1983). Since then, no other logging practices have been performed and today the forest is in the so-called demographic transition stage (FRELICH, 2002), passing from an impressive single-layer canopy to a multi-cohort structure. The forest of REG is represented by a mixed stand of *Fagus sylvatica* and *Quercus ilex* and its preservation from massive logging was linked to the presence of an historical spring providing freshwater to the contiguous town of Roccantica (PIOVESAN *et al.*, 1996). Grazing is still present today in the lower borders of the forest.

2.2. *Structural analysis and dead wood*

Structural analyses were generally conducted using circular plots with a 20 m radius (all the Apennines stands and Lateis, LAT), with the exception of the steepest Alpine site (Timau, TIM), where the radius of the sampling plots was 10 to 20 m. Within each stand, circular plots were positioned with a systematic criterion in order to cover most of the old-growth forest area. The average distance among plots was 100 m. However, due to the presence of a rugged topography and/or the fragmentation of the forest area in several

nearby small stands, the distance among plots varied between 70 and 150 m. In the small stand of Fonte Regna (Table 1) a transect of 30 x 180 m was made within the core area.

Structural features (stems per ha, basal area, volume, diameter distribution) about living trees of the Alpine sites Gracco (GRA) and Cleulis (CLE) were instead obtained from Forest Management Plans (FMPs); information about dead wood structure was lacking in FMPs.

In each plot, for each tree species we measured Diameter at Breast Height (DBH, measured at 1.3 m from the ground) on trees with DBH > 2.5 cm (DBH thresholds vary for FMPs data: see Table 2). Heights were measured on a representative number of trees of all diameter classes to build height-DBH curves. For each tree, linear distance from the plot center and the azimuthal angle from the North were measured (polar coordinates). Basal area and volume distributions in DBH classes were determined, with a special attention to the relative amounts of both parameters attributable to the largest DBH classes. Volume of living trees was calculated with the two-way volume table for *Fagus* in Italy (CASTELLANI *et al.,* 1984) except for CIM where the one-way volume table for *Fagus* of Calabria (I class of fertility) was used (SGADARI, 1961).

Dead wood was divided into its standing and fallen components, called respectively snags and Coarse Woody Debris (CWD: logs and branches). Only downed debris with median diameter (D_{med}) ≥ 10 cm were ascribed to CWD, while those with D_{med} < 10 cm were defined as Fine Woody Debris (FWD). FWD were further divided into two dimensional classes: FWD_{2-10}, with D_{med} in the range 2-10 cm; FWD_{0-2}, with D_{med} < 2 cm.

Dead wood structure was determined for each site by recording the number and diameter distribution of snags and CWD. Polar coordinates, DBH and height of snags with DBH ≥ 10 cm were measured; for truncated snags volume was calculated according to the formula:

$$V = g * h$$

where g = basal area, h = snag height. Instead, for unbroken standing dead trees we used the two-way table for *Fagus* in Italy (CASTELLANI *et al.,* 1984).

Polar coordinates and median diameter (D_{med}) were measured for all CWD (D_{med} ≥ 10 cm). CWD volume was calculated according to Huber's formula (FRIDMAN and WALHEIM, 2000):

$$V = s_{0.5} * l$$

where $s_{0.5}$ = median sectional area and l = length.

Each element of dead wood (snags or CWD) was referred to a decay class ranging from class I to V with decreasing integrity (RUBINO and MCCARTHY, 2003).

Table 2 – Structural features of the study sites (t_{DBH}=diameter sampling threshold; N=number of stems per hectare; $N_{17.5}$=number of stems per hectare with DBH>17.5 cm; Stature=mean height of the 5 tallest trees; G=basal area per hectare; V=woody volume per hectare; DV/TV=Dead to Total volume (live + dead volume) ratio; Age_{max}=number of rings counted on the oldest tree; Age_5=mean age of the 5 oldest trees (yrs); Period=calendar years corresponding to the first and last measured ring).

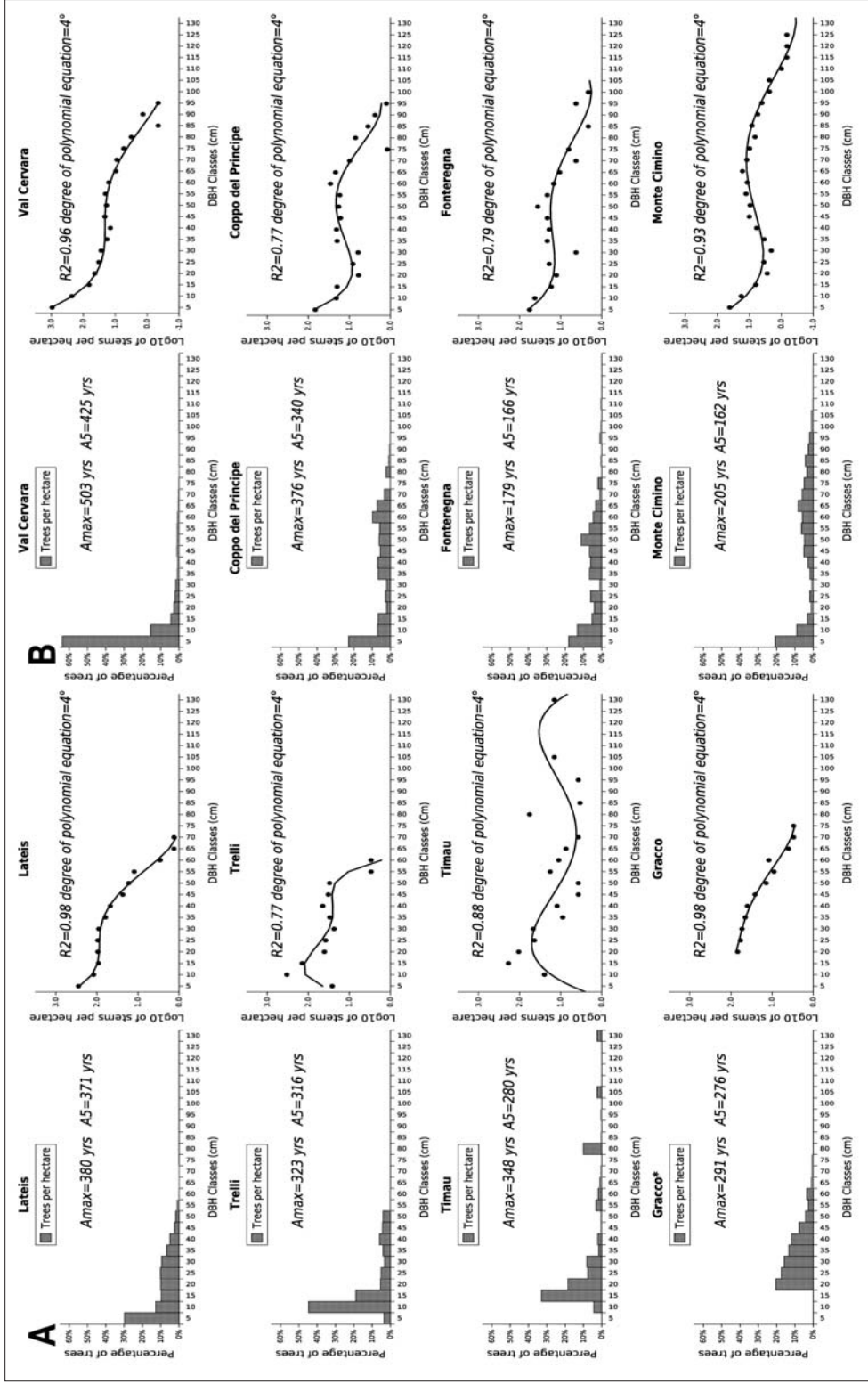| Site | Live trees structure | | | | | | Dead trees structure | | | | Age structure | | | |
	t_{DBH} (cm)	N (n ha⁻¹)	$N_{17.5}$ (n ha⁻¹)	Stature (m)	G (m² ha⁻¹)	V (m³ ha⁻¹)	Dead volume	Snags (m³ ha⁻¹)	CWD (m³ ha⁻¹)	DV/TV (%) (m³ ha⁻¹)	Cores	Age_{max} (yrs)	Age_5 (yrs)	Period
							Alpine stands							
LAT	2.5	878	505	30	40	533	18	5	13	3.3	28	380	371	1625-2004
TRL	2.5	741	244	21	29	319	16	9	7	6.9	22	323	316	1686-2008
TIM	7.5	568	356	33	40	647	–	21	–	–	27	348	280	1655-2002
GRA	17.5	336	336	21	34	302	–	–	–	–	20	291	276	1685-2002
CLE	2.5	430	–	24	35	394	–	–	–	–	23	260	209	1744-2003
							Apennine stands							
VCH	2.5	1590	239	28	41	497	65	24	41	11.6	32	503	425	1500-2002
COP	2.5	296	188	32	44	715	91	37	54	11.3	30	376	340	1633-2008
REG	2.5	317	446	32	42	540	42	24	18	7.3	20	179	166	1830-2008
CIM	2.5	197	132	46	48	707	19	5	14	2.6	33	205	162	1804-2008

Figure 1 – Diameter distribution of Alpine (A) and Apennine stands (B).

FWD$_{2-10}$ was sampled using the line-intercept method (VAN WAGNER, 1968). At each site, three to six 50 m-long lines were sampled. According to this method, the volume per unit area (m^3 m^{-2}) is:

$$V = 9.869* \Delta (d^2 / 8L)$$

where d is the piece diameter (m), and L is the line length (m). For the FWD category, each element was referred to a decay class ranging from I to III with decreasing integrity (D'ANDREA, 2008):

– Class I, 100% wood basal density (for beech, 0.600 Mg m^{-3});
– Class II, 66% wood basal density (0.396 Mg m^{-3});
– Class III, 33% wood basal density (0.198 Mg m^{-3}).

FWD$_{0-2}$ was estimated at each site by collecting all pieces in fixed area plots (1 m^2). At each site, three random sub-plots in each 20 m radius circular area were sampled.

When presenting each stand structural feature, Alpine and Apennines sampled stands were ranked according to the Age$_5$ parameter (see *Dendroecological analysis* for explanation).

2.3. Carbon stocks in ecosystem compartments

2.3.1. Biomass

Aboveground biomass of stems and major branches was estimated by converting the volume values given by two-way tables for beech (CASTELLANI *et al.*, 1984) or one way table in the case of Cimino (SGADARI, 1961) using the wood basal density measured at a montane forest in Central Italy (Collelongo; SCARASCIA MUGNOZZA *et al.*, 2000).

At selected sites, leaf biomass was assessed using litter traps. Ten to twenty 0.5 m^2 circular litter traps were installed at CIM and REG. Litter was collected three times at the end of the growing season. Litter was brought back to the laboratory dried, weighed and three samples per site were analysed for Carbon and Nitrogen content (see under Chemical analysis).

For belowground biomass, the detailed allometric equations of Collelongo montane beech forest were used to estimate stump, coarse root (diameter > 2.5cm), medium root (from 1.5 to 2.5 cm of diameter) and small root (from 0.5 to 1.5 cm of diameter) biomass (MASCI, 2002).

Conversion of biomass to carbon was made by using carbon content measured on the relevant component or literature data (BAUER *et al.*, 2000).

2.3.2. Litter

Accumulation of litter on the ground was determined during summer on randomly distributed positions. Samples of forest floor were obtained by pressing a 0.09 m^2 quadrat sampling frame into the forest floor and collecting

all organic material of horizons L and F above the mineral soil. The L horizon is composed of fresh or slightly discoloured material, with no or weak breaking up. The F horizon is composed of medium to strongly fragmented material with many mycelia and thin roots. The number of samples was 18 for CIM, 12 for REG, 12 for COP, 8 for LAT, 8 for TIM.

2.3.3. Soil

At each site, after a preliminary series of coring to unravel diagnostic soil horizons, a representative soil profile was opened and described according to SCHOENEBERGER *et al.* (2002). Sampling was performed according to horizons using minipits and corer. Approximately 10 samples per horizon were collected. Horizon bulk densities were determined in the field, using cylinders of known volume. Three replicates per horizon were performed.

Samples were brought to the laboratory, oven-dried at 60° C to constant weight and sieved (2 mm) to separate the coarse fraction (> 2 mm) from fine earth (< 2 mm). Soil texture was estimated using the pipette method on three replicates per soil horizon, while pH was determined on all samples in water.

Soil carbon stock (SOC, kg C m^{-2}) was calculated using the following equation (BOONE *et al.* (1999):

$$SOC = a * b * c * d$$

where a = C concentration in the sample (kg C kg_{soil}^{-1}), b = bulk density (kg_{soil} m^{-3}), c = soil depth (m), d = 1 - coarse fraction

2.3.4. Chemical analysis

All chemical analyses were performed with an elemental analyser Carlo Erba NA1500 (Milano, Italy) on dried and milled samples. In the case of soils, samples were homogenised to less then 0.5 mm. Carbonates were removed by using a 10% HCl solution.

2.4. Dendroecological analysis

A minimum number of 20 cores were sampled in each site to perform dendroecological analyses. Trees were cored at breast height with a Pressler's increment borer: in TRL, COP, REG and CIM canopy trees representative of all DBH classes were cored, while in LAT, TIM, GRA, CLE and VCH, sampled in previous dendroclimatic studies, only dominant-codominant trees were available. A total of 235 cores were sampled in the period 2002-2008 (120 cores for Alpine stands; 115 for Apennines stands). Cores were mounted, sanded and polished and ring-widths measured to the nearest 0.01 mm using

CCTRMD (Computer Controlled Tree Ring Measure Device; ANIOL, 1987) and the software CATRAS (ANIOL, 1983). Finally tree-ring series were dated after visual and statistical crossdating (STOKES and SMILEY, 1996).

Cores reaching the pith were used to investigate DBH-age relationships and to analyze age influence on forest structure. The age refers to 1.30 m. Maximum age (Age_{max}) was defined for each stand as the age of the oldest tree, but the parameter Age_5 (mean age of the 5 oldest trees per stand) was used to rank all stands according to their age.

The *boundary line* (BLACK and ABRAMS, 2003) for beech in the Italian peninsula was built considering 57796 pairs of ten-years averaged *Percent growth change* (%GC) and *Prior growth* (PG) values derived from 15 Italian beech stands (10 in the Eastern Alps and 5 in Central Italy) to detect moderate and major radial growth releases related to the occurrence of ecological disturbances (*data not shown*). Disturbance events, dated according to the *boundary line* release criteria (distinguished into moderate and major events), were organized into decades. Disturbance chronologies for 2 old sites in the Eastern Alps and 2 in the Apennines were developed. Finally, the growth history and release events of the 3 oldest trees in VCH and LAT (the oldest stand on the Apennines and the Alps, respectively) were presented to describe the disturbance history's influence on growth patterns on the oldest individuals.

2.5. *Carbon isotope discrimination analysis*

Isotope ratio measurements were performed on both leaf material and tree-rings obtained from wood cores. WUE dynamics were thus reconstructed for the last decade. Each isotopic series was related to dendrological data on an individual base. Particularly, isotopic analyses in this study were performed on wood cores from 3 Central Italy sites: Monte Cimino (CIM), Fonte Regna (REG) and Coppo del Principe (COP). Six trees for each site were considered, for a total of 18 cores. For the period 1999-2008, each growth ring was isolated, finely ground and analysed for carbon isotope composition. The individual isotopic series obtained were matched to Basal Area Increment (BAI). Given the possibility of a reciprocal memory effect between BAI and Δ of contiguous years (GAGEN *et al.*, 2006; MCDOWELL *et al.*, 2003), possible regressions were explored shifting the two series of one year in the two possible combinations. Litter material was also collected in COP and CIM and analysed for carbon isotope composition. Irrespective of the material, sub-samples of about 500 g were quantitatively burned in an elementar analyser (NA 1500, Carlo Erba). The produced CO_2 was admitted in a helium continuous flow to an isotope ratio mass spectrometer (CF-IRMS; ISOPRIME, GW, UK). Sample isotope ratios were measured to allow the

calculation of carbon isotope composition ($\delta^{13}C$) referred to the IAEA standard VPDB. Carbon isotope discrimination (Δ) was then calculated using the classical formula reported by FARQUHAR *et al.* (1989; see also LAUTERI *et al.*, 2004) and taking into account $\delta^{13}C$ values of atmospheric CO_2 from international databases (NOAA, IPCC). The parameter Δ contains a fundamental comparative and normalization significance. Thus it allows ecophysiological comparisons among conditions that are different in time and space. Δ is widely used and accepted as a powerful proxy of Water Use Efficiency (WUE).

3. RESULTS

3.1. Live trees structure

Density of old-growth forests varies significantly from the Alps to the Apennines (Table 2). Alpine stands are characterized by values of stem ha^{-1} ranging from 336 to 878, but considering only those stands in which sampling threshold is DBH>2.5 cm (LAT, TRL, CLE) this range reduces to 430-878 stem ha^{-1}. In the Apennines stand density is generally lower (296 - 317 stem ha^{-1}) but reaches its peak in VCH (1590 stem ha^{-1}) which presents the most developed forest structure. Alpine stands have in general lower stature, passing from 21 m in TRL to 33 m in TIM; on the other hand, in the Apennines, beech forests show higher stature (28-46 m), sometimes impressive like in Monte Cimino, where some individuals can even be higher than 50 m. Basal area ranges from 29 to 40 m^2 ha^{-1} in the Alps, but less variation characterizes the Apennines beech forests, with values oscillating from the minimum of 41 m^2 ha^{-1} of VCH to 48 m^2 ha^{-1} of CIM. Mean volume of living trees ranges from 302 m^3 ha^{-1} to 647 m^3 ha^{-1} in the Alpine stands, and from 497 m^3 ha^{-1} to 715 m^3 ha^{-1} in Apennine stands.

In all sampled stands diameter distribution in 5 cm DBH classes was described, after log transformation, by a polynomial equation as suggested by GOFF and WEST (1975) for old-growth forests (Fig. 1). In each stand a fourth degree polynomial equation best fit the DBH logarithmic distribution, generating a "rotated sigmoid" ("*diameter distributions characterized by steep decreases in tree density in the smallest and largest diameter classes and a plateau in the middle diameter classes that becomes more pronounced when displayed on semilogarithmic axes*", from JANOWIAK *et al.*, 2008) in the oldest stand on the Apennines (VCH) and the Alps (LAT), and a bimodal distribution in the other stands. Volume distribution among DBH classes tends to be normally distributed everywhere (except in TIM), negatively skewed in the Apennine stands, where large amount of woody volume are concentrated in the larger DBH classes (*data not shown*).

3.2. Dead trees structure

Presence of dead wood inside sampled old-growth forests varies greatly, depending on the single stand structural development, but also on the fact that often in the past CWD was removed from the forest to be used as fuelwood. This may explain the lower amount of deadwood observed in comparison to other old-growth forests in northern Europe and in the USA (see *Discussion*). The smallest amount of total dead trees volume are found in the Alps (TRL, 16 m³ ha⁻¹ and LAT, 18 m³ ha⁻¹; dead trees volumes for GRA and CLE were not reported in the FMPs). In central Italy total deadwood volume was lower in the secondary old-growth forests of CIM (19 m³ ha⁻¹) and REG (42 m³ ha⁻¹), but reached larger amounts in high-elevation old-growth forests of VCH and COP (65 and 91 m³ ha⁻¹, respectively). CWD represents the most important components of dead wood in most of the sampled stands (63-83% of total deadwood volume), while snag volume exceeds CWD volume only in TRL and REG.

3.3. Carbon stocks

Preliminary results on carbon stocks on a subset of sites are presented in Fig. 2 for different ecosystem compartments. The data indicate that these old-growth forests are relevant carbon reservoirs, with 192-268 MgC ha⁻¹ of total biomass (67-73% aboveground; 27-33% belowground, 4 stands) and 7-21 MgC ha⁻¹ of deadwood. In these stands, also forest floor (excluding
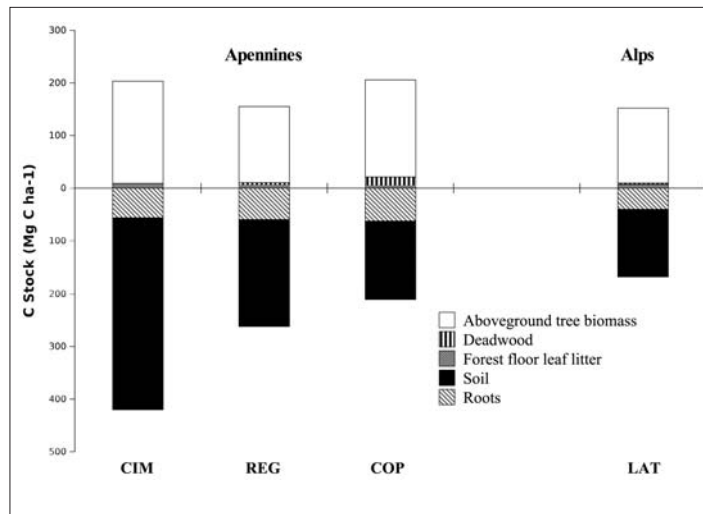

Figure 2 – Living biomass, deadwood, litter and soil carbon stocks for selected sites within the Italian old-growth beech forests network. Sites are ordered according to their age (Age₅).

deadwood) and soils are stores of relevant amount of carbon (5-9 MgC ha^{-1} litter layer, 4 stands; 168-420 MgC ha^{-1} mineral soil, 4 stands).

Among the sampled forest, CIM is the stand with the largest C stock, mainly due to the carbon stored in the soil.

Tree biomass represents from 37% (CIM) to 53% (COP) of total carbon pools, while deadwood makes up 1% (REG) to 4% (COP) of all ecosystem compartments. Soil and litter carbon stocks are very important at all sites sampled so far, with LAT and COP having 46% and 43% of total carbon stored in those compartments, while at CIM and REG soil and litter stocks represent 62% and 54% of the overall eco-system C stocks.

Biomass of branches is reported as far as this component is included in the tables used for volume calculation. However, tables are generally derived from even-aged stands, generally younger and with different structure and development compared to old-growth stands. In this respect, within the PRIN project, an original methodological approach is being developed for the assessment of crown volume and biomass. Preliminary results at CIM and COP indicate that the crown of trees is old-growth forest has a larger volume and biomass compared to the crown of trees with similar diameter but grown in even-aged stands (*data not shown*).

3.4. Dendroecological analysis

Among the sampled stands VCH is by far the oldest, reaching a maximum age of 503 years; LAT, TIM, TRL and COP host various individuals older than 300-350 years; in GRA, CLE and CIM maximum age fall between 200 and 300 years, while at REG age doesn't exceed two centuries (179 years). The Age$_5$ parameter (mean age of the 5 oldest trees in each stand), allows a better distinction between old-growth forests in advanced structural development and secondary old-growth forests (CIM and REG). Most sampled stands exceed at least half of the maximum lifespan of beech (~ 500 years in VCH).

By plotting present DBH against age no significant relationships emerges between the two variables in the oldest stands (e.g. VCH, COP, LAT, TRL) (Fig. 3) and this is due to the growth history of cored trees (PIOVESAN *et al.,* 2005b). The DBH-age-growth graph of Fig. 3 shows clearly that trees from old-growth forests like VCH and COP and old stands such as LAT and TIM present a wide range of growth patterns, while other stands show a more regular evolution of growth through time that could be linked to a lower density (e.g. CIM, REG and GRA). Furthermore, in the secondary old-growth forest of CIM the dominance of the central cohort is evident, characterized by a biostatic structure (100-150
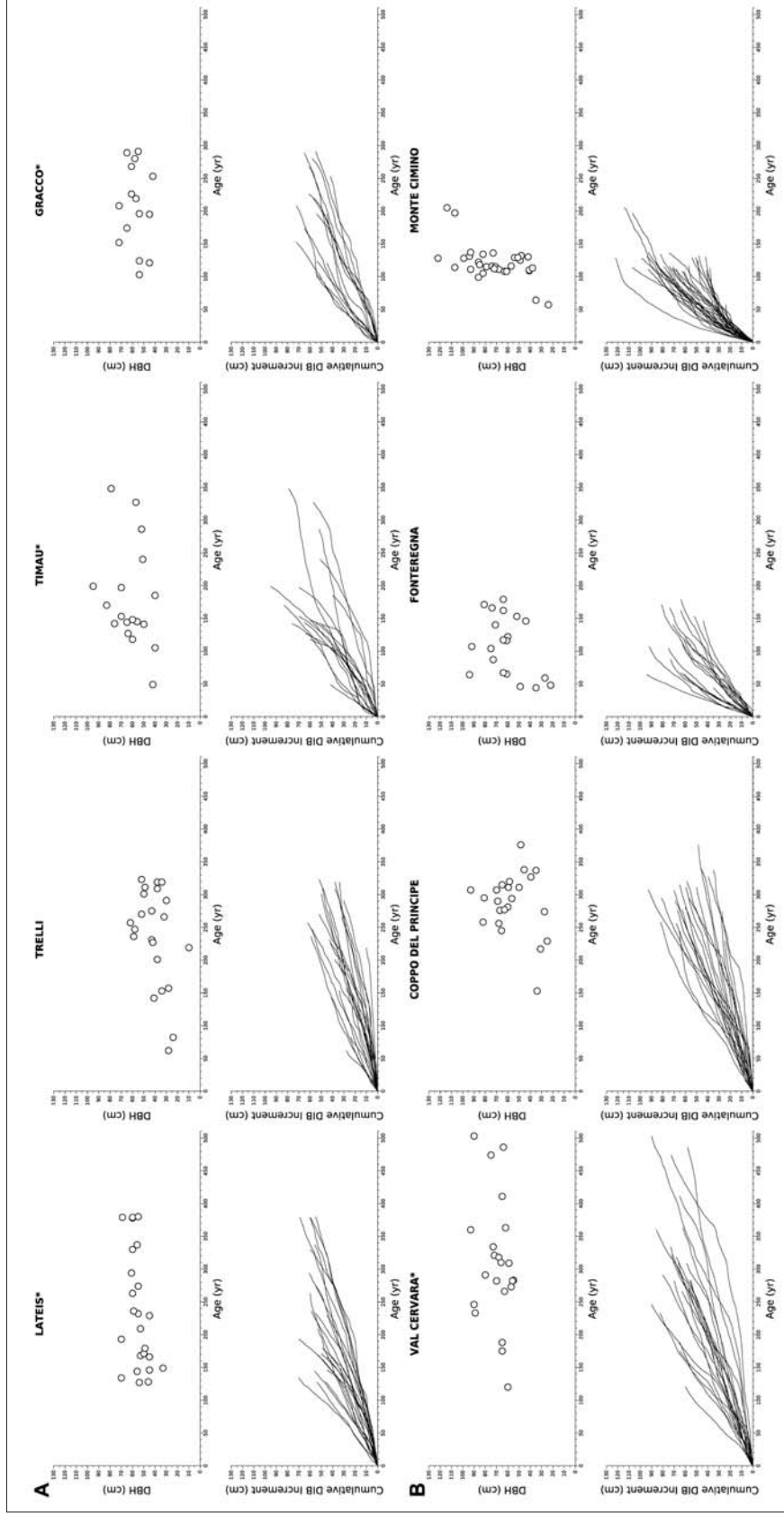
Figure 3 – Age-DBH relationships and auxological history of Alpine (A) and Apennine stands (B). For each site, the graph above represents the age-DBH relationship, while the lower one represents the cumulative Diameter Inside Bark (DIB). * = stands in which only dominant trees were cored.

years old) in a wide DBH range; at the same time in REG there is interesting evidence of different growth rates for younger dominant trees and older dominated individuals.

Disturbance chronologies built for LAT-GRA in the Alps and VCH-COP in the Apennines showed that in all cases old-growth beech forests experience a disturbance regime based on frequent low-to-moderate severity events (Fig. 4): release and recruitment events are present in almost all decades from 1700 to 2000, with most events involving no more than 10-20% of cored trees. Peaks of disturbances found in the Alps (e.g. 1850-1869 and 1940-1949) and in the Apennines (e.g. 1760-1769; 1820-1829; 1880-1889) could be probably synchronized in different stands by climatic events (see PIOVESAN *et al.,* 2005b).

Tree-ring series of the six oldest individuals in LAT and VCH confirmed that during their life these trees experienced few moderate disturbance events or gradual release events (Fig. 5). Often the first events occur in advanced age, meaning that the oldest beech trees were able to survive for several decades in the understorey.

3.5. Isotopic analysis

Mean Δ values recorded in the wood cores in the decade (1999-2008) were relatively different among the sites (Table 3). Coppo del Principe (COP) showed the highest Δ and Fonte Regna the lowest. The average value of CIM is intermediate. Δ values in leaf litter are higher than those of wood cores, in both COP and CIM. This finding is somewhat surprising, given the ^{13}C depletion of lignin in wood material (WILSON and GRINSTED, 1977; LEAVITT and LONG, 1982), but was previously reported in another study (WEITNER *et al.*, 2007).

The analysis of C stable isotopes in tree rings, as expressed in Δ notation in relation to BAI across the referred decade, reveals an interesting negative relationship (Fig. 6A) in COP and REG when comparing shifted pairs of BAI (year *n-1*) versus Δ (year *n*). A non significant, but tendentially

Table 3 – Comparison of values of Δ in tree rings (average of 6 cores containing tree-rings from 1999 to 2008), litter (sampled on the ground in 2009) and BAI for the three sites analysed in Central Italy; mean values ± standard errors. Uppercase letters indicate significance difference of the same variable among sites.

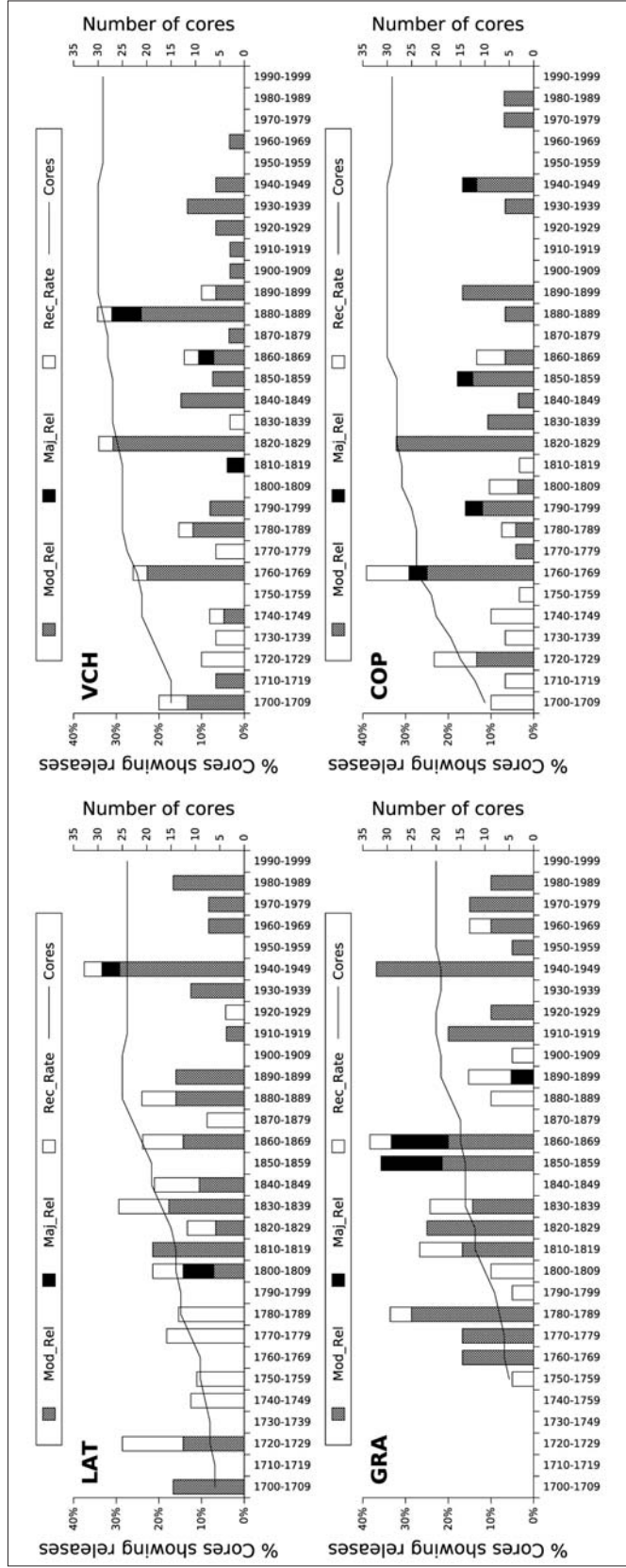|	*Coppo del Principe*	*Monte Cimino*	*Fonte Regna*
Δ tree rings (‰)	18.4 ± 1.3[a]	18.3 ± 0.6[a]	17.8 ± 1.1[b]
Δ litter (‰)	20.2 ± 0.0	20.7 ± 0.2	–
BAI (cm² yr⁻¹)	23.08 ± 1.23[a]	41.73 ± 2.44[b]	38.43 ± 2.27[c]

Figure 4 – Disturbance chronologies for two Alpine (left) and two Apennine stands (right) for the period 1700-1999: white bars represent recruitment rate expressed (Rec_Rate) as percentage of total cored trees born in a given decade; grey bars are moderate releases (Mod_Rel); black bars are major releases (Maj_Rel). The final number of cores differs from Table 2 because of damaged or incomplete cores which required the exclusion of related series.
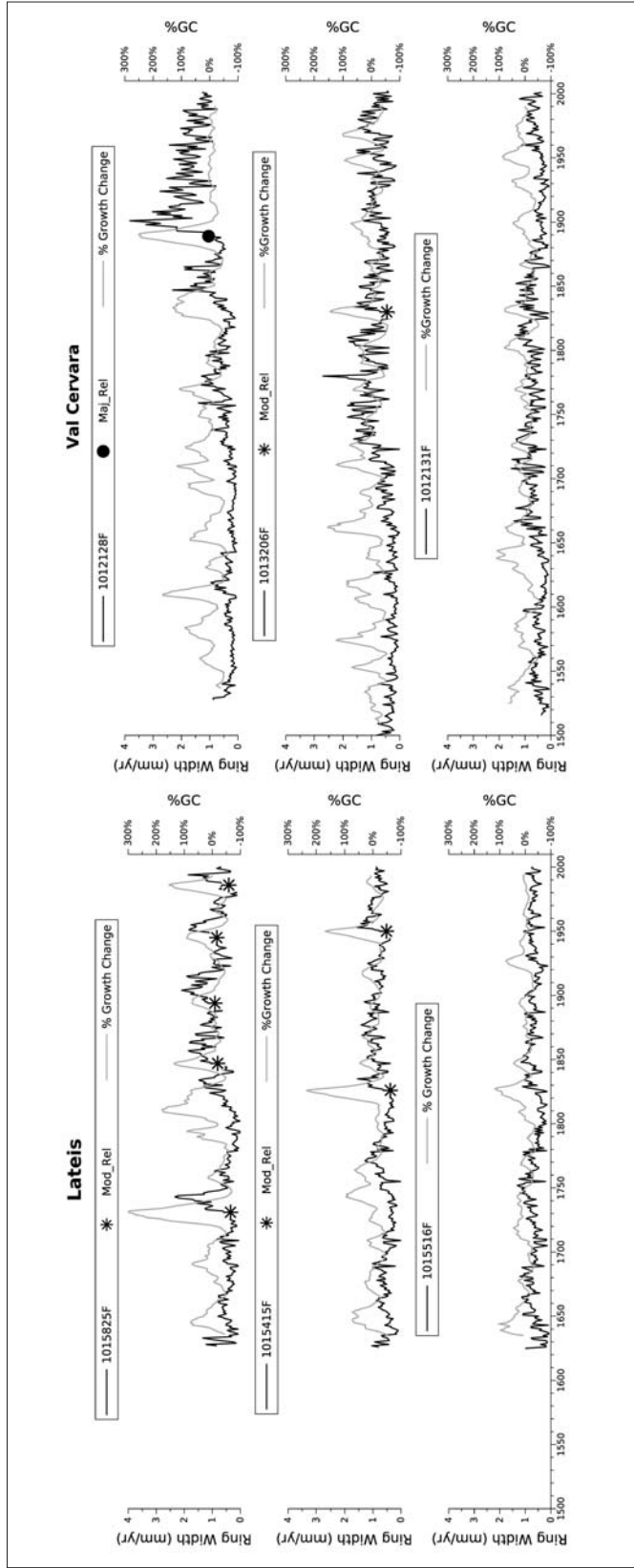
Figure 5 – Ring-widths chronologies and disturbance events for the three oldest trees at LAT and VCH, detected according to the boundary line release criteria (Mod_rel = moderate releases; Maj_rel = major releases). Horizontal lines above each series represent gradual release events not detected by the boundary line method.
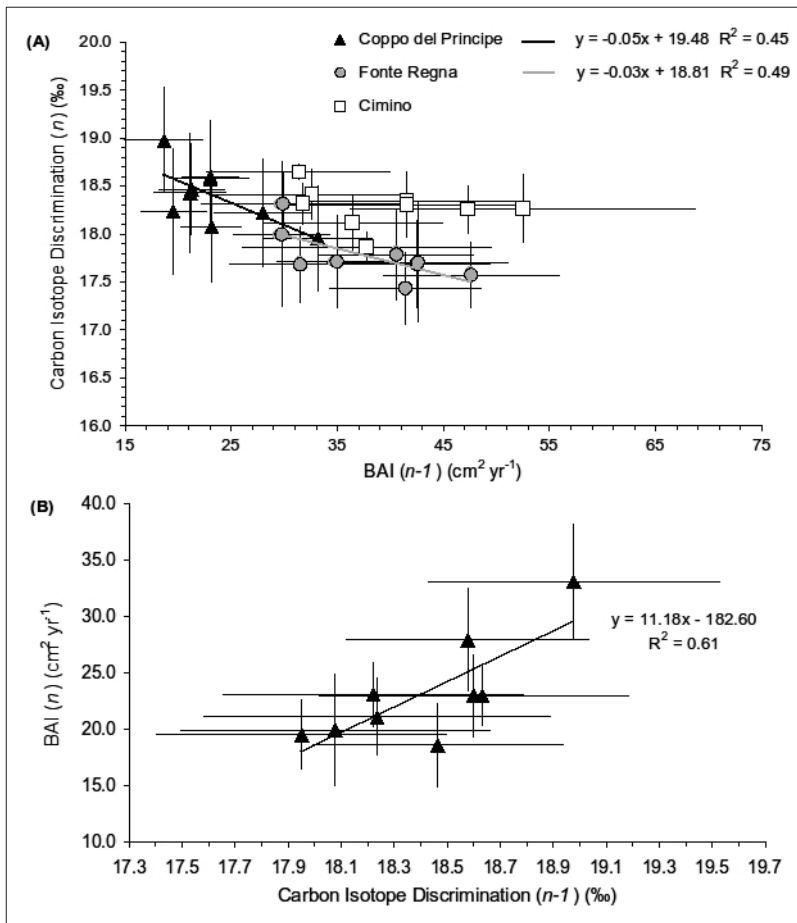
Figure 6 – Relationship between   in tree rings and BAI. Each data point it's the average of values from 6 trees for each year in the period 1999-2008. (A) Relationship between   values of year "*n*" and BAI values of year "*n-1*" for the 3 Apennines sites; in the case of CIM the regression is not significant; dotted line represents the standard error of the mean. (B) Coppo del Principe. Relationship between BAI values of year "*n*" and   values of year and "*n-1*".

negative regression was observed for CIM. Thus, low Δ values are related to high BAI values. On the other side, it is noteworthy that the three analysed populations are quite clearly separated in the graph, on the basis of both Δ and BAI values. Such a negative regression would imply, in the classical Δ analysis, that high WUE is linked with high BAI, given the well tested negative relationship between WUE and Δ (BRUGNOLI and FARQUHAR, 2000).

It is, finally, noteworthy that a significant positive regression (Fig. 6B) was found relating BAI (year n) to Δ (year n-1) just for the old-growth population of COP.
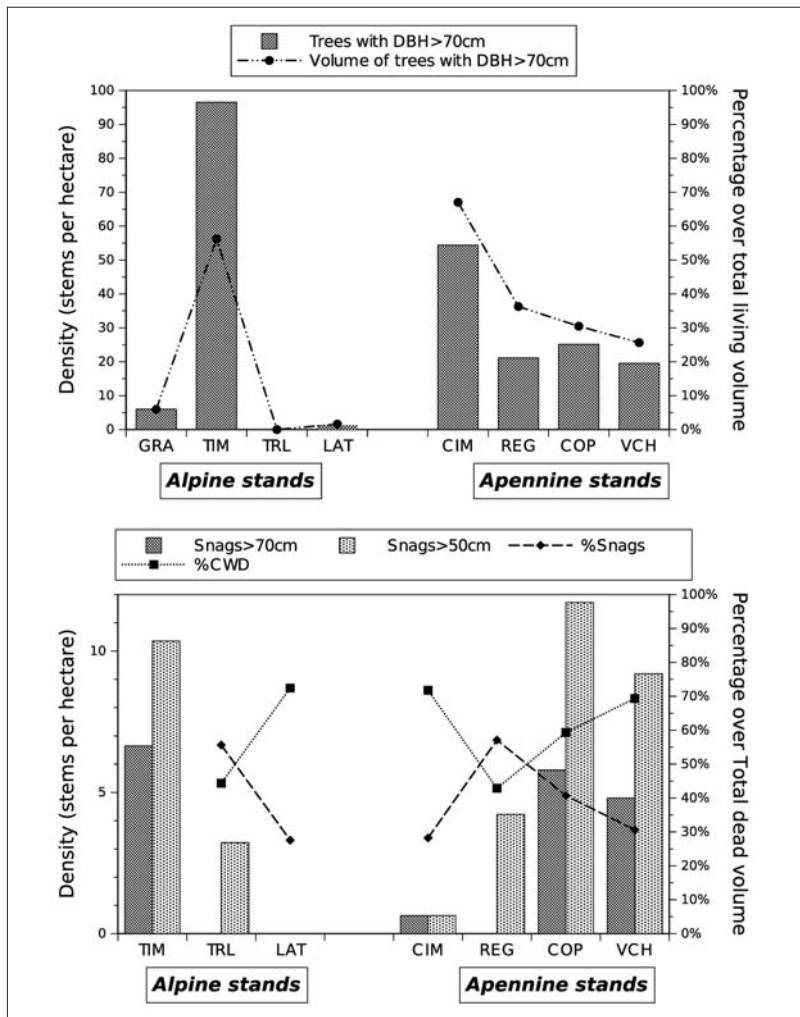
Figure 7 – Old-growthness indicators. (Above) Large trees (DBH ≥ 70 cm): density and their volume percentage on total living volume. (Below) Snags density and dead volume partition among snags and CWD.

4. DISCUSSION

In defining old-growth forests, a detailed analysis of pattern and processes is required. A combination of structural and botanical features may serve as important indicators (e.g. GOFF and WEST, 1975; TYRRELL and CROW, 1994; KEDDY and DRUMMOND, 1996; GREENBERG *et al.,* 1997; PONTAILLER *et al.,* 1997; EMBORG *et al.,* 2000; NILSSON *et al.,* 2002; DEBELJAK, 2006) as well as the dendroecological reconstruction of forest

dynamics (NAGEL *et al.,* 2007). Forest naturalness could be expressed through a 'gradient' based on the gradual appearance of those structural features and processes typical of primitive stands that are lacking or insufficiently represented in managed forests (GILG, 2004). Therefore, the 'old-growthness' of a given stand can be defined to describe the degree of development of old-growth structural features (SPIES and FRANKLIN, 1988) and considered a synonym of 'naturalness'. Evaluating the degree of old-growthness even of a single stand could be extremely costly in terms of time, money and knowledge required (BAUHUS *et al.,* 2009) because of the high number of indicators that could potentially be considered. Practically, it is preferable to follow a 'structural-based approach' for detecting old-growth attributes, since structure represents a "*readily measured surrogate for functions (e.g. productivity) and for organisms (e.g. cavity-dwelling animals) that are difficult to measure directly*" (FRANKLIN *et al.,* 2002). A representative set of structural indicators has to be chosen (TYRRELL and CROW, 1994; WHITE and LLOYD, 1994; KEDDY and DRUMMOND, 1996; GREENBERG *et al.,* 1997; BAUHUS *et al.,* 2009) and the number of parameters to be measured needs to be adequately dimensioned. To assess old-growthness in the sampled beech stands we first considered four groups of indicators: basal area and volume of the stand; density of large living trees (DBH>70 cm) and their contribution to total basal area or volume; presence and volume of standing and downed dead trees, with special attention to large trees; diameter distribution (Tab. 2; Figs. 1 and 7).

Values of basal area exceeded in all stands the control/normal limit (>29 m^2 ha^{-1}) proposed by KEDDY and DRUMMOND (1996) for old-growth mesic hardwood deciduous forests. Mean volume per hectare is high in all stands with values comparable to those reported for other old-growth beech forests (see PIOVESAN *et al.*, 2005b for a review).

Another important old-growth feature is represented by the density of large trees, which account for a large portion of total volume in old-growth forests (BROWN *et al.,* 1997; GREENBERG *et al.,* 1997; NILSSON *et al.,* 2002; PIOVESAN *et al.,* 2005b). Control value is given by NILSSON *et al.* (2002), who found in *Fagus* dominated forests of Central Europe a density of living trees with DBH >70 cm of about 30 stem ha^{-1}. Apennine old-growth forests approach the control value of 25-30 stem ha^{-1} (maximum value in the site of CIM with 54 stem ha^{-1} with DBH > 70 cm) (Fig. 7). On the Alps very few individuals with DBH > 70 cm, except in TIM, where we found a large number (97) of stems ha^{-1} with DBH > 70 cm (Fig. 7). Consequently only in the Apennine stands (with the above mentioned exception of TIM) large percentage of volume are concentrated in the largest diameter classes and the reference value of at least 20% of total woody volume included in classes with DBH > 70 cm suggested by BROWN *et al.* (1997) for old-growth forests

is reached. This discrepancy between Alps and Apennines could be interpreted as the consequence of both forests' history and site conditions. Highest values of density and volume of large trees (DBH > 70 cm) are found in CIM and REG, both characterized by fertile soils that experienced in the past at least one period of low-density grazed forests, in which canopy structure was mainly composed by large-sized scattered trees. Occurrence of large trees in the primary old-growth forest of VCH and in COP could be partially linked to mean age of the oldest trees (Age$_5$) of these stands, exceeding 340-400 years (even if there isn't a direct relationship between age and DBH). On the other hand, most of the Alpine stands grow on extremely steep slopes, often close to conditions of rocky soils, where diameter enlargement is limited by nutrient supply and rocky and steep topography.

Dead wood is a fundamental component of natural forests (see CHRISTENSEN *et al.*, 2005) and it is among the most important indicators to distinguish *natural* from *managed* forests (DEBELJAK, 2006), as a consequence of reduced or no logging activities (EMBORG *et al.,* 2000; VON OHEIMB *et al.,* 2005). CWD is central for maintaining a wide range of ecosystem's functions and services (STEVENS, 1997) and its importance relies largely on relative abundance, state of decay and pieces size, which influences its use by the biota (PYLE and BROWN, 1999). In a review on dead wood amounts over 86 beech forest reserves across Central Europe, CHRISTENSEN *et al.* (2005) found that mean dead wood volume was 130 m^3 ha^{-1} with a high level of variation (from ~0 to 550 m^3 ha^{-1}); PIOVESAN *et al.* (2005b) reported a range of 50-200 m^3 ha^{-1} for pure *Fagus* forests in Europe. Among sampled stands, only VCH and COP have total amounts of dead wood comparable to cited values (65 and 91 m^3 ha^{-1} respectively); lower amounts were found in REG (42 m^3 ha^{-1}); the other showed values ranging around 16-19 m^3 ha^{-1}. This scarcity of deadwood is related to CWD removal made in the past in several stands (e.g. CIM, LAT, TIM). Abundance of deadwood in natural forests varies greatly depending on the present structural phase (DEBELJAK, 2006). LEIBUNDGUT (1993, cited in WOLYNSKI, 2001) argues that deadwood volume should approach 10-15% of total live plus dead trees volume in adult stands, increasing up to 25-30% in the ageing phase. In any case, Alpine and Apennine beech forests reach these percentages, with the highest deadwood/total volume ratio found in VCH and COP (~11%). In most stands CWD (logs and stumps) contributes more than snags to dead volume, according to the results of previous studies reporting that snags represent about 20-40% of total dead trees volume (NILSSON *et al.*, 2002). However, the density of large snags (DBH > 70 cm) is, especially on the old-growth beech stands of the Apennines, within the range values (NILSSON *et al.*, 2002).

Diameter distribution is a key structural feature to describe natural forests and interpret their growth history (PONTAILLER *et al.,* 1997; EMBORG

et al., 2000; VON OHEIMB *et al.,* 2005). Despite diameter distributions of old-growth stands have been traditionally described with a reverse J-shaped curve (see WESTPHAL *et al.,* 2006 for a review), various findings suggested a 'rotated-sigmoid' curve being more reasonable for describing tree-sizes distribution in old-growth forests (GOFF and WEST 1975; ZHANG *et al.,* 2001). By investigating diameter distributions in nine virgin beech forests of south-eastern Europe, WESTPHAL *et al.* (2006) showed how rotated-sigmoid curves derived from a Weibull function are able to fit the observed diameter distributions better than the negative exponential function, which usually underestimate the number of stems in the midsize diameter classes. The appearance of rotated-sigmoid curves has been linked to asymmetric U-shaped mortality trends found in mature and old-growth stands (LORIMER *et al.,* 2001) where highest mortality rates are experienced by the smallest individuals, as a consequence of self-thinning (COOMES *et al.,* 2003), and by large dominant trees, which are more exposed to natural disturbances (LORIMER *et al.,* 2001). Intermediate size trees, instead, undergo lower mortality rates (GOFF and WEST, 1975). This trend in mortality rates generates a plateau in the midsized classes (see WESTPHAL *et al.,* 2006; JANOWIAK *et al.,* 2008). In our study sites rotated-sigmoid curves are evident only in those stands with the higher degree of naturalness (e.g. VCH and partially LAT) (Fig. 1). The other stands showed a bimodal distribution, generated by a two- or few-cohort stage, typical of the "demographic transition" stage (FRELICH, 2002), where numerous patches in the innovation-aggradation phases are present (EMBORG *et al.,* 2000).

Disturbance regime directly influences auxology of forest stands, their structural dynamics, and deadwood volume and contribute to shaping the resulting forest mosaic. Anyway, disturbance frequency and distribution have been probably altered by human impacts, since few forests escaped logging (DI FILIPPO *et al.,* 2005). From dendroecological analyses performed on sampled old-growth forests emerged a distinction between those stands with a higher degree of "old-growthness" (VCH-COP-LAT-TIM) and secondary old-growth forests (e.g. CIM), where a single cohort is clearly distinguishable (Fig. 3). Primary old-growth stands (e.g. VCH) have a multi-aged structure, typical of the last stages of stand development (FRELICH, 2002) and related to fine-scale disturbance regime in temperate deciduous forests (GILG, 2004). Disturbance chronologies produced for four of the oldest relatively undisturbed stands by using the boundary line release criteria (BLACK and ABRAMS, 2003) present the dominance of low-severity disturbances scattered in several decades from 1700 to 1999 (Fig. 4). These findings underline the importance of gap dynamics in maintaining beech forests, more than stand-replacing events, which instead would synchronize recruitment rates and canopy accessions (PIOVESAN *et al.,* 2005b). Beech is in fact well adapted to a

small gap disturbance regime thanks to its physiological and morphological plasticity (CANHAM, 1988; WAGNER *et al.*, 2010). Anyway the presence of synchronous peaks in disturbance events, as occurred in VCH and COP in the 1760 and 1820 does not exclude a certain role of periodic intermediate severity events (e.g. windstorms), which could contribute to the creation of multiple tree gaps (NAGEL *et al.,* 2007). Beech adaptation to gap dynamics is testified by the analysis of growth patterns of the oldest individuals (Fig. 5). Tree-ring series of old trees showed very low increments for several decades (suppression) and one or more disturbances (multi-gap episodes), marked on tree-rings as ecological releases. Besides multi-gap episodes, typical of late-successional old-growth forests (PIOVESAN *et al.*, 2005b), in some cases gradual, instead of abrupt, growth releases were observed, revealing the presence of very low-severity, progressive disturbance events releasing the crown of surviving trees.

The data on C stocks available for the project's sites sampled and analysed so far indicate that the studied forests are characterised by relevant values of biomass, deadwood and soil carbon stocks. The data presented here for total biomass (400-540 Mg ha^{-1}, excluding deadwood and soils) are at the highest portion of the range of other available data for managed beech forests in Europe (157-468 Mg ha^{-1}, 23 studies, closed stands, age 54-270) (MATTEUCCI *et al.*, 1999). Mean tree carbon pool in much denser unmanaged stands sampled recently in Spain ranged between 280 and 320 MgC ha^{-1} (Fig. 3 in MERINO *et al.*, 2007) compared to our range of 192-268 MgC ha^{-1} (that include only a portion of crown biomass). However, data on total ecosystem C stocks of the four forests sampled in our study (377-695 MgC ha^{-1}) are higher than the mean range reported for Spain (350-400 MgC ha^{-1}). Nevertheless, soil C in the sampled old-growth beech forests in Italy (168-420 MgC ha^{-1}) is higher than the mean values reported for Spanish unmanaged forests on different soils (40-125 MgC ha^{-1}) (MERINO *et al.*, 2007) and similar in range to that reported for mature beech forests sampled in Germany along a precipitation gradient on a similar geological substrate (MEIER and LEUSCHNER, 2010). When calculated over 30 cm soil depth, the soil C data of this study are within the range reported for beech forests in Japan (LI *et al.*, 2010). Nevertheless, data measured at CIM are among the highest reported for beech forests.

Finally, C isotope discrimination analyses on tree rings from old-growth beech forests revealed interesting retrospective informations on ecophysiological performances. Indeed, the 3 analysed populations (CIM, REG, COP) are quite clearly separated on the basis of both Δ and BAI values. From previous dendroclimatic investigations (e.g. PIOVESAN *et al.*, 2005a), COP can be ascribed to the high-elevation beechwood, where summer drought control on growth was limited and was important the April-May

temperature; CIM and REG, both pertained to a transition group between mountain and low-elevation beechwoods where summer drought is the main climatic signal. Despite the difference in elevation, the high-elevation COP and the beechwood growing on fertile volcanic soils (CIM; see also WEITNER *et al.*, 2007) showed a higher Δ than the calcareous REG (living at the same elevation of CIM). The fact that Fonte Regna is characterised by relatively low Δ and high BAI, could indicate a relatively dry site (causing high WUE) with favourable temperature supporting an active growth through a well extended vegetative season. Accordingly to this double parameter interpretation (GAGEN *et al.*, 2006), CIM seems affected by both favourable growth temperature (relatively high BAI) and water availability thanks to the fertile soils (high Δ). Finally, COP forest shouldn't have been limited by intense and long summer drought (high Δ) along the decade, but would have been constrained by sub-optimal temperatures for most of the vegetative seasons. This hypothesis is supported by the positive relation between Δ of the previous year (*n-1*) and BAI of the current one (*n*). Such a relation was found in this high-mountain population, but not for the other two transitional populations (REG and CIM). This effect would be visible in the population COP which is especially limited by the shortness of the vegetative period, but not in those (REG and CIM) characterized by a longer growing season and the likely occurrence of drought periods. Indeed, the presence of the positive correlation between BAI and previous year Δ at COP, could indicate the importance of reallocation of previous year assimilates on current tree productivity. Furthermore, all the three Apennine populations showed no significant relationships between concurrent growth (BAI) and WUE, as inferred from Δ analysis. The physiological response in terms of Δ seems to be partially and negatively controlled by the growth of the previous year. In fact, vigorous growth at year *n-1* would increase the likelihood of drought constraints at year *n*, resulting in a decreased Δ because of crown expansion and consequent major exposure to the atmosphere. Whether or not these observations are consistent within a wider span of populations and ecological conditions, the capability to discriminate different sites on the basis of both physiological (Δ) and dendrochronological features (BAI) appears noteworthy.

5. CONCLUSIONS

Among all sampled stands only VCH can be defined as a primary old-growth forest because, besides the lack of evidence of sylvicultural inter-vention, its structural attributes satisfy the control values and dendro-

ecological (Age$_{max}$, Age$_5$, growth patterns and disturbance chronologies) as well as historical analyses (e.g. chronosequences of aerial photos) confirmed that its dynamics were driven by natural processes for centuries. The remaining stands, which have not yet fully acquired advanced old-growth features, might be considered as secondary old-growth forests with different degree of naturalness, from the most developed (LAT, TRL) to the youngest ones (REG and CIM). Further historical investigations are needed to fully understand the degree of naturalness of COP.

Our study shows how defining old-growth forests following a "structural-based approach" does not allow foresters to unambiguously mark the border between old-growth forests and managed stands, since structural development is extremely complex (FRANKLIN *et al.,* 2002). Nonetheless the structural approach provides an overview on those parameters (e.g. basal area and volume distribution; large trees; deadwood) involved in defining the naturalness degree of a given forest (GILG, 2004) or, in other words, its 'old-growthness' (SPIES and FRANKLIN, 1988). Moreover, it is based on easy-to-measure attributes, which are of great help when dealing with economical restrictions for monitoring programs. The importance of the "structural-based approach" relies also on the fact that some of the mentioned structural indicators may act as functional indicators, indicating the occurrence of old-growth related processes (e.g. mortality of dominant senescent trees), thus providing a fundamental tool for assessing and monitoring old-growth forest ecosystems.

All the forests sampled within the project are important carbon reservoirs, both at tree and soil compartments. Carbon stocks of these forests are generally higher than other managed stands, both in Italy and Europe. A combined analysis enclosing both ecophysiological and dendrochronological data, if properly tuned with climatic series, could aid in reconstructing the past environmental scenarios of old-growth beech forests and their response to a varying climate. In this respect, the use of multiple sampling and research techniques and the integration of research groups with complementary expertise can foster deeper understanding of the ecology and dynamics of old-growth forests.

RIASSUNTO

Analisi strutturale, processi di crescita e *stock* di carbonio in una rete italiana di faggete vetuste

Nell'ambito del progetto PRIN «Cambiamenti climatici e foreste - Risposte dendroecologiche ed ecofisiologiche, produttività e bilancio del carbonio in una rete italiana di faggete vetuste», sono state analizzate 9 faggete delle Alpi orientali e dell'Appennino centrale per determinarne: i) il grado di vetustà su base strutturale e dendroecologica; ii) gli *stock* di carbonio (C) nei diversi comparti ecosistemici; iii) una caratterizzazione ecofisiologica sulla base degli isotopi stabili. In alcune tra le più vecchie e meno disturbate faggete italiane sono state esaminate: la struttura delle piante vive e della necromassa; le caratteristiche del suolo; e gli *stock* di C. Inoltre foglie, lettiera e carote legnose sono state campionate per le analisi dendroecologiche, dei nutrienti e degli isotopi stabili, per studiare la struttura per età, sviluppare cronologie di disturbo, valutare le risposte climatiche di medio e lungo termine ed investigare alcuni aspetti ecofisiologici.

In tutti i popolamenti studiati i valori di area basimetrica, volume e il numero di grandi alberi per ettaro sono confrontabili con quelli di riferimento riportati per foreste vetuste europee e nord-americane, mentre il quantitativo di necromassa presente è generalmente basso, eccetto nei due siti più naturali. Le distribuzioni diametriche variano tra curve bimodali e la sigmoide-ruotata. Le analisi strutturali e le cronologie di disturbo rivelano l'importanza di eventi di medio-bassa severità nel generare una struttura a scala fine, confermando precedenti risultati ottenuti in foreste di faggio. Diversi gradi di 'vetustà' sono stati identificati per le faggete alpine ed appenniniche attraverso un approccio "strutturale", che si è dimostrato un valido strumento per l'individuazione delle foreste vetuste.

Risultati preliminari sugli *stock* di carbonio, ottenuti in un sottocampione di popolamenti, indicano come tali foreste vetuste siano rilevanti riserve di carbonio, con 192 - 268 MgC ha^{-1} di biomassa (67-73% nella parte epigea; 27-33% nella parte ipogea; 4 popolamenti) e 7 - 21 MgC ha^{-1} nella necromassa. In questi popolamenti anche lettiera (esclusa la necromassa) e, soprattutto, suolo stoccano notevoli quantitativi di carbonio (5 - 9 MgC ha^{-1} nella lettiera, 4 popolamenti; 168 - 420 MgC ha^{-1} nel suolo, 3 popolamenti). Infine l'analisi della discriminazione isotopica del carbonio (Δ), un indicatore dell'efficienza di uso idrico, è stata condotta su carote legnose estratte da un sottocampione di siti; sono state quindi descritte le prospettive di questa tecnica per una interpretazione ecofisiologica retrospettiva degli impatti del cambiamento climatico sulle foreste vetuste.

I risultati preliminari ottenuti nell'ambito del progetto PRIN indicano come gli indicatori ecologici utilizzati possano essere usati per produrre valide descrizioni delle strutture forestali e dei processi che guidano le dinamiche dei popolamenti ('approccio strutturale'). L'utilizzo di tecniche di campionamento multiple e l'integrazione di diversi gruppi di ricerca con competenze complementari può inoltre favorire una più profonda conoscenza dell'ecologia e delle dinamiche delle foreste vetuste.

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