

# Tree rings used to assess time since death of deadwood of different decay classes in beech and silver fir forests in the central Apennines (Molise, Italy)

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**Abstract:** We investigated the relationship between time since death and morphological characteristics of *Abies alba* Mill. (European silver fir) and *Fagus sylvatica* L. (European beech) stumps in two forest stands in the central Apennines. At each site, 15 or 16 living trees were selected, and increment cores were collected to build master ring-width chronologies. For both sites, cross sections were collected from stumps. Samples were assigned to visually discernible decay classes, and their death date dendrochronologically determined. Using cross-dating techniques, stumps cross-dated significantly with standard chronologies, and it was possible to assign a year of death to 77% and 69% of sampled *A. alba* and *F. sylvatica* stumps, respectively. Analysis of the time since death of the stumps suggests that the two species have similar decay rates, although *A. alba* was faster in passing from class 2 to class 3. However, this study revealed a continuum through decay classes and showed a high variability in the transition rate from one class to another. Overall, information obtained using dendrochronological techniques was valuable for assessing deadwood decomposition rates. The variability found in stump decomposition rates indicates that existing decay classification schemes, although providing information on decomposition timing, are hardly applicable to these forest stands and that the relationship between qualitatively assessed decay classes and time since death of trees appears to be rather weak.

**Résumé :** Nous avons étudié la relation entre les caractéristiques morphologiques des souches d'*Abies alba* Mill. et de *Fagus sylvatica* L. et le temps écoulé depuis leur mort dans deux peuplements forestiers situés dans l'Apennin central. Dans chaque station, 15 ou 16 arbres vivants furent choisis et des carottes furent prélevées pour construire des dendrochronologies de référence. Dans les deux stations, des tranches radiales furent prélevées sur des souches. Les échantillons furent assignés à des classes de décomposition visuellement identifiables et l'année de la mort des arbres a été déterminée par dendrochronologie. À l'aide des techniques de datation croisée, la datation croisée des souches avec les chronologies standards était significative et il a été possible d'assigner une année de mort à respectivement 77 % et 69 % des souches d'*A. alba* et de *F. sylvatica* échantillonnées. L'analyse du temps écoulé depuis la mort des souches indique que les deux espèces ont un taux de décomposition similaire, même si *A. alba* passe plus rapidement de la classe 2 à la classe 3. Cependant, cette étude a révélé qu'il y avait un continuum d'une classe de décomposition à l'autre et une forte variation du taux de passage d'une classe à l'autre. Dans l'ensemble, les informations obtenues à l'aide des techniques dendrochronologiques ont été précieuses pour évaluer le taux de décomposition du bois mort. La variation observée dans le taux de décomposition des souches indique que les façons de procéder utilisées pour établir la classe de décomposition, bien qu'elles fournissent des informations au sujet du rythme de décomposition, sont difficilement applicables à ces peuplements forestiers et que la relation entre les classes de décomposition identifiées de façon qualitative et le temps écoulé depuis la mort des arbres semble plutôt faible.

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## Introduction

Deadwood is a very important component in forest ecosystems. Although its ecological role has been recognized

for a long time (Haapanen 1965), only recently has research focused on its role in ecosystems and considered it a key structural factor (Larsson 2001), reflecting also the increasing importance in forest inventories for assessment and re-

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porting. Deadwood is also a crucial indicator for assessing the biodiversity and naturalness of forest systems (McComb and Lindenmayer 1999), because it is a microhabitat for hundred species of invertebrates (Siitonen 2001), fungi (Heilmann-Clausen 2001), bryophytes (Ódor and Standovár 2001), lichens (Humphrey et al. 2002), amphibians (Raymond and Hardy 1991), small mammals (Loeb 1999), and birds (McComb and Lindenmayer 1999). The quantity of deadwood occurring in natural forest depends on the forest type, its development stage, the frequency of natural or anthropogenic disturbances in the region, and local soil and climatic characteristics. These all influence the formation and decay cycles of deadwood (Christensen et al. 2003). In particular, deadwood plays an important role in long-term carbon storage (Cairns and Meganck 1994). Therefore, when focusing on the potential of forest ecosystems for carbon sequestration, the carbon cycle and the role that forests play in regional and global carbon budgets should be well understood.

Besides fossil fuel burning, the reduction in carbon storage in forest is one of the most critical factors responsible for the increase of CO<sub>2</sub> in the atmosphere (Harmon et al. 1990). Currently, the release of carbon from land-use changes and forest activities through the decay of residual biomass is calculated according to the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC 2001). However, these estimates of CO<sub>2</sub> emissions are subject to large uncertainties that result from a wide range of sources including the rate at which litter and woody debris decay. This information is important for monitoring the rate of sequestration and emission in forest inventories. The IPCC default estimate for the decay of aboveground litter appears to be based on too rough an estimate of actual carbon losses from decaying wood, primarily because it does not take into account the climatic and environmental variables controlling decomposition. Indeed, we need to know much more about the contribution of deadwood to the forest carbon cycle on regional and global scale.

If multifunctional forest management and planning are to integrate biodiversity- and CO<sub>2</sub>- related goals at various levels, reliable estimates of decay rates for different tree species are needed. Estimates have been provided for numerous species occurring naturally in North America (Tyrrel and Crow 1994) and in Europe (Siitonen 2001; Christensen et al. 2003). However, decay rates for montane species at Mediterranean latitudes are largely missing (Marchetti and Lombardi 2006). To infer long-term effects of forest management practices, the time frame of deadwood decomposition through a series of decay classes can be quantified through integrated models (Vanderwel et al. 2006). However, too little data are currently available to allow for any broader generalization about the relationship between latitude and decay rates (Storaunet and Rolstad 2002).

Tree-ring analyses and <sup>14</sup>C ages have been used to measure the time since death of individual fragments of deadwood at different levels of decay (Daniels et al. 1997; Kueppers et al. 2004). Relationships between the time since death of trees and the level of decay of deadwood have been established in North America (Daniels et al. 1997; Brown et al. 1998), but this type of investigation has rarely been attempted in Europe (but see Storaunet 2004). In this study,

tree-ring analyses and dendrochronological techniques have been used to ascertain the time since death of *Abies alba* Mill. (European silver fir) and *Fagus sylvatica* L. (European beech) stumps that died naturally and to explore the relationship between the time since death of stumps and several morphological characteristics typically described in the field (Hunter 1990) during forest inventory surveys. Our final aim was to test an objective method for tracking the rate of progression of wood decay in *A. alba*, a softwood species, and *F. sylvatica*, a representative hardwood species, which are two of the most widespread trees in the mountain forests of Southern Europe.

## Materials and methods

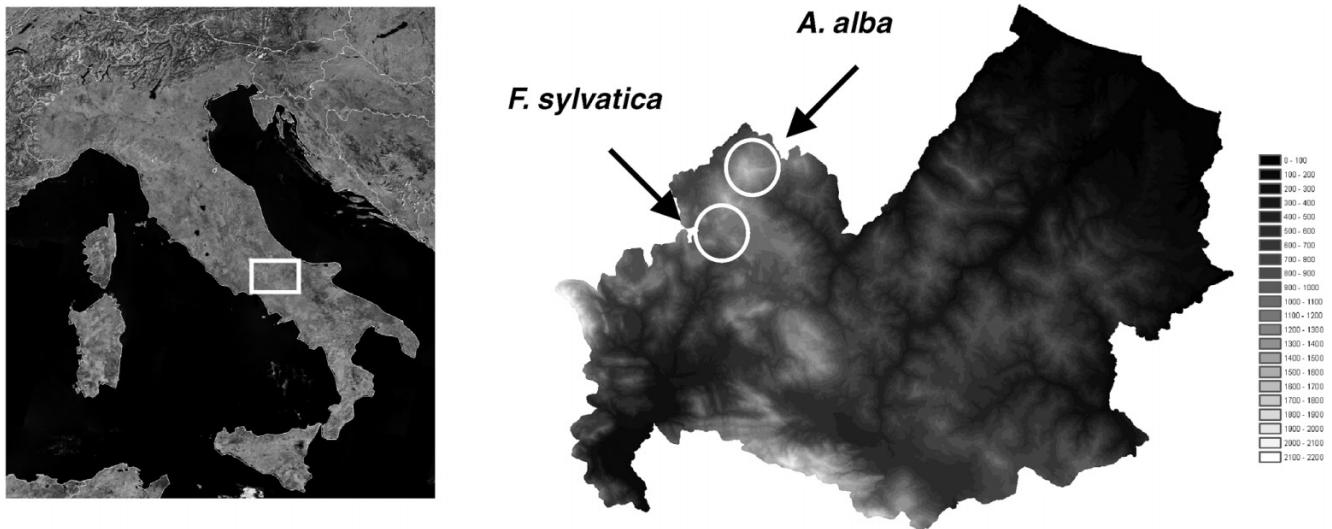
### Site description

Cross-sections of *F. sylvatica* and *A. alba* from stumps, and cores from living trees were sampled in two mountain sites located in the Apennines in the Molise Region (Italy) (Fig.1). The two sites, considered representative of montane beech and coniferous forests of the Mediterranean, Anatolian and Macaronesian regions (EEA 2006), are located within a 10 km radius of each other and both are within the temperate bioclimatic region, humid mesotemperate type. Both sites are characterized by a rich macrofauna, with the presence of the wolf, weasel, stone marten, badger, fox, hare, boar, red woodpecker, and hawk (Abbate 1990). Thus, they are important sites in the context of the EU Natura 2000 network.

The silver fir site is located in the forest “Abeti Soprani,” near Pescopennataro, a small village close to Isernia, 160 km east of Rome. The study area is located at an elevation ranging from 1000 to 1450 m a.s.l. The slope is north facing, and the geology is dominated by Miocenic-clay soils and Cretacic white limestone. Rendzina soils are also prevalent (Ferrari and Wolf 1970). The mean annual temperature at the nearest meteorological station is 8.4 °C, with an annual mean precipitation of 1124 mm (1927–1987). January is the coldest month, and July is the warmest month; mean temperatures are –0.1 °C and 18.0 °C, respectively. The forest is a relict stand dominated by *A. alba*, typical of the fir forests currently widespread in the Mediterranean and Anatolian regions. Its structure and composition are similar to that common in the past throughout the Apennines, but which nowadays survive only in small areas of the Italian peninsula (Ciancio et al. 1985). *Aquifolium-Fagetum*, subassociation *abietetosum albae* (Abbate 1990), is the dominating vegetation syntaxonomic unit: the forest is an almost pure *A. alba* stand, sometimes associated with *F. sylvatica* at the highest altitudes and with *Quercus cerris* L. at the lowest altitudes. In the community, other species such as *Acer pseudoplatanus* L., *Acer campestre* L., *Acer obtusatum* Waldst. et Kit. ex Willd., *Taxus baccata* L., *Carpinus betulus* L., *Tilia platyphyllos* Scop., *Ulmus glabra* Huds., *Pyrus pyraeaster* Burgsd., *Fraxinus ornus* L., *Sorbus torminalis* (L.) Crantz., and *Malus sylvestris* Mill. occur.

The European beech site is located in the “Montedimezzo” protected area, close to Vastogirardi, a small town in the Isernia province. The site is part of the MaB United Nations Environmental, Scientific and Cultural Organization Reserve of “Collemeluccio-Montedimezzo,” a forest area

**Fig. 1.** Location of *Fagus sylvatica* (Apennine–Corsican montane beech forest; EEA 2006) and *Abies alba* (Mediterranean and Anatolian fir forest; EEA 2006) sites (circles) in the Molise Region (rectangle and magnification on the right), Italy. Elevations above sea level are shown using the scale on the right.



that has been unmanaged since 1950. The study area is located at an elevation ranging from 920 to 1240 m a.s.l. The slope is north facing, and the geology is dominated by Cretaceous limestone, with greensands and clay soils prevalent. The mean annual temperature at the nearby-located meteorological station is 8.6 °C, with an annual mean precipitation of 1022 mm (1980–1991). January is the coldest month, and July is the warmest month; mean temperatures are 1.5 °C and 17.0 °C, respectively. The structure of this Apennine–Corsican montane beech forest is very diverse, containing all phases of the forest life cycle. Stumps and decaying wood are still present near saplings. *Polistycho aculeati–Fagetum sylvaticae aceretosum pseudoplatani*, *Acer lobelii*, *Aquifolio–Fagetum fraxinetosum excelsioris*, *Aquifolio–Fagetum abietetosum albae* types (Abbate 1990) are the dominating vegetation units. The forest is a beech stand, associated with *Q. cerris* at the lowest altitudes and sometimes mixed with other species such as *Acer pseudoplatanus*, *Acer campestre*, *Acer obtusatum*, *Taxus baccata*, *C. betulus*, *Tilia platyphyllos*, *U. glabra*, *P. pyraeaster*, *Fraxinus ornus*, and *S. torminalis*.

### Sampling protocol

Fieldwork was carried out in summer 2006. At each site, one area of approximately 2 ha was identified and 15 or 16 living dominant and codominant trees were selected, with diameters at breast height ranging from 58 to 87 cm (mean 73 cm) and heights around 24 m. Care was taken to select trees with canopies well separated from each other to reduce the effect of competition on tree growth. Two increment cores were taken with an increment borer 0.5 cm in diameter from each tree uphill at height of 1.3 m at an angle of 120° to each other. Cores were mounted on channeled wood, seasoned in a fresh-air dry storage and sanded a few months later.

In the same areas, cross sections were taken from the stumps of trees that had died naturally. Generally, stumps high ranges from 20 to 40 cm. In total, 45 *A. alba* and 54 *F. sylvatica* cross sections were sampled. All cross-sections

were 6–7 cm thick. For each stump, the diameter at the top was measured. Considering that deadwood composition and shape are strongly influenced by many factors that affect the rate of decay, such as slope aspect and soil moisture (Harmon et al. 1986), and log diameter (MacMillan 1988), each site was chosen taking into account the common requirements for a regular slope and comparable soil characteristics. Cross sections from stumps were always taken near the ground. Smaller stumps typically decompose faster than larger stumps. To have a long reconstruction period but also to include the small stumps that are frequent in the studied stands, stumps  $\geq 10$  cm in diameter at stump height were selected. Cross sections were stored in a fresh-air drying chamber and sanded a few months later, after which ring-width measurements were carried out.

### Decay classification

The level of decay of the stumps allows a rough relative estimate of the number of years since tree death. The assignment of each stump to a decay class in the field was based on a visual assessment of stump morphological characteristics. Stumps were classified according to the five-class system described by Hunter (1990), based on decay levels with a five-point scale, which has become widely used in Europe because of the ForestBiota (2004) and BioSoil (2006) projects. This system is based on morphological wood features, based essentially on the presence of bark and the integrity of wood structure. Tree rings have to be visible to measure ring widths, to allow the cross-dating, and to assign a tree-death date to each stump. Therefore, it was possible to sample only the first three classes proposed by Hunter (1990), and classes 4 and 5 were not included in this study.

In the Hunter classification system, class 1 is characterized by stumps that have intact bark and the wood still hard with an intact structure and the wood's original color. In class 2, the bark is broken up into patches and has partly fallen off, but the wood still maintains its structural integrity, although the outer layers of the stumps have started to soften because of rot. However, the wood still maintains its

original color. In class 3, the bark is completely absent, all wood structure has started to soften, the soft outer layers disintegrate easily (knife test), the core is still solid, and the color has normally already started to fade.

The stage of decay can vary in different parts of the stump; when more than one class of decay was present on the same stump, we used the most widely represented decay class in the cross section taken at the top of the stump.

### Ring-width measurement, cross-dating procedure, and statistical analyses

Tree rings were dated by counting them from bark to pith. Ring widths were measured to the nearest 0.01 mm using the LINTAB measurement equipment coupled to a stereomicroscope (60 $\times$  magnification; Leica, Germany). The time series analysis programme software package (Frank Rinn, Heidelberg, Germany) was used for statistical analysis. Raw ring widths of the single series of each dated trees were plotted, checked visually, and then cross-dated statistically by the percent agreement in the signs of the first differences of the two time series (the *Gleichlaufigkeit*, GLK; Kaennel and Schweingruber 1995). The GLK is a measure of the year to year agreement between the interval trends of two chronologies based on the sign of agreement or the sum of the equal slope intervals in percent. With an overlap of 50 years (which is commonly used in tree-ring studies), GLK becomes significant ( $p < 0.05$ ) at 62% agreement and highly significant ( $p < 0.01$ ) at 67%. With an overlap of 10 years, GLK becomes significant ( $p < 0.05$ ) at 76% agreement and highly significant ( $p < 0.01$ ) at 87% (Kaennel and Schweingruber 1995). In our work, the analyzed time series were mostly longer than 50 years, and cross-dating was considered successful if GLK was  $>60\%$ .

The statistical significance of the GLK (GSL) was also computed. The TVBP, a Student's  $t$  value modified by Baillie and Pilcher (1973) and further developed by Munro (1984), was used for investigating the significance of the best match identified. The TVBP is commonly used as a statistical tool for comparing and cross-dating ring widths series. It determines the degree of correlation between curves. This method eliminates low-frequency variations in the time series, because each value is divided by the corresponding 5 year moving mean.

Locally missing or discontinuous rings were identified by cross-dating the two tree-ring cores obtained from the same tree. Standard methods (Fritts 1976) were used to build a tree-averaged series and the two mean site chronologies using ring-width series obtained from each of the 15 or 16 living trees growing at the two study sites. The year of death of each stump was determined by identifying the calendar year in which the outermost ring of each tree was formed (Dynesius and Jonsson 1991; Mast and Veblen 1994; Cherubini et al. 2002). The ring width of stumps was cross-dated when possible, always assigning a calendar year to the outermost ring. The cross-dating procedure involved matching a ring-width series from dead cross sections of unknown date of death to a dated ring-width series, i.e., the site chronology. Stump chronologies were visually and statistically cross-dated to reference chronologies by GLK, taking into account GSL and TVBP, with the same procedure used for living chronologies (Fritts 1976).

The length of the matched sample depended on (i) the number of rings that could be measured, (ii) the stage of decay of stumps (old stumps with much sapwood lost could not be cross-dated), and (iii) the quality of the rings measured (missing or false rings) (Dynesius and Jonsson 1991). Not all the stumps sampled could be dated. Stumps with less than 20 rings often could not be cross-dated; in some cases, advanced levels of decay, fragmentation, or mechanical damage made ring-width measurement impossible. To understand the relationship between time since death and decay classes, the mean of the year of death for each class of decay in both species was compared. The distribution of each population was tested using the Kolmogorov–Smirnov normality test (Dagnelie 1973, 1975). If the result of the normality test was positive, parametric comparison methods were adopted; otherwise, nonparametric comparison tests were assumed (Dagnelie 1973, 1975; Sprent 1992). Two-sample  $t$  tests and nonparametric Mann–Whitney tests were used on independent samples to compare decay classes.

## Results

### Living trees

The basic statistics of chronologies built with living *F. sylvatica* and *A. alba* trees and the study sites' characteristics are presented in Table 1.

The time interval of *F. sylvatica* curves extended from 1843 to 2005 (Fig. 2). All but two single-core ring-width series for the living beech trees were cross-dated with their mean; GLK values were always highly significant ( $p < 0.001$ ). They also showed a TVBP value which was always higher than 6.4, and very often higher than 14. The two chronologies that did not cross-date significantly were not considered in further analyses.

In the case of mean living *A. alba* chronologies (Fig. 2), four single-core ring-width series were not cross-dated successfully with their mean, and thus, they were not used for further analysis. A total of 25 *A. alba* cores were cross-dated significantly with their mean, with highly significant GLK values ( $p < 0.001$ ) in all cases, except one with  $p < 0.01$ . They also always had a high TVBP value of around 9. The time interval of *A. alba* curves extended from 1840 to 2005.

The *F. sylvatica* and *A. alba* sites are about 10 km away from each other (i.e. they are not very close), but we still compared and cross-dated the mean chronologies of the two sites (Fig. 2). In both sites, there were no trees older than 160 years, and their growth patterns had different trends in the first 30 years (1840–1870). Afterwards, the trends were very similar, as shown in Fig. 3. GLK values were very high (72%,  $p < 0.001$ ), and the TVBP value was 5.5. The two curves displayed a good synchronicity of negative (e.g., 1904, 1908, 1929, 1932, 1958, and 1963) and positive peaks (e.g., 1868, 1877, 1893, 1906, 1964, 1976, 1990, and 1996), although *F. sylvatica* appears to be more sensitive than *A. alba*. In the mean chronology of *A. alba*, there was a step around 1908 because of an increment in growth rates.

### Year of tree death

The year of tree death was defined as the year in which the last growth ring or partial ring was produced by the tree. At the study sites, it was possible to assign a year of

**Table 1.** Characteristics of living trees and cross sections taken from stumps at *Fagus sylvatica* and *Abies alba* sites.

Species	No. of trees	No. of cores	DBH (cm)	Height (m)	Altitude (m asl)	Facing	Slope (%)	Max. age (years)	Decay class 1			Decay class 2			Decay class 3		
									No. sampled	No. dated	DBH (cm)	No. sampled	No. dated	DBH (cm)	No. sampled	No. dated	DBH (cm)
<i>A. alba</i>	15	30	58–84	20–26	1300–1350	North	10–20	175	24	18	12–65	28	24	11–71	18	12	12–63
<i>F. sylvatica</i>	16	32	63–87	22–28	1100–1150	North	5–15	162	15	11	11–61	30	17	13–57	20	17	10–65

death to 77% and 69% of the sampled stumps for *A. alba* and *F. sylvatica*, respectively. It was not possible to use dendrochronological methods on cross sections older than 60 years, because wood samples tended to crumble during the sanding process. The main characteristics of the sampled and dated stumps are presented in Table 1. All sampled stumps were cross-dated with standard chronologies built at each site using living trees. For each stump, the most recent date determined by cross-dating is reported in Table 2 for *A. alba* and in Table 3 for *F. sylvatica*.

Overall, the correlation coefficients for cross-dating the *A. alba* stumps were highly significant (Table 2). Stumps in decay class 1 had highly significant GLK values ( $p < 0.001$ ) for 10 of 18 samples (Table 2). With the samples in decay class 2, cross-dating of exactly one-half of the samples were highly significant ( $p < 0.001$ ) and the remaining samples cross-dated significantly with standard chronologies of living trees (Table 2). Finally, 12 samples in decay class 3 (Table 2) were significant at  $p < 0.001$  in cross-dating. For *A. alba*, the GLK values in cross-dating were also always high, often around 70%.

Cross-dating *F. sylvatica* stumps was also highly significant (Table 3). Stumps in decay class 1 cross-dated significantly with living standard chronologies. The GLK values were highly significant ( $p < 0.001$ ) for five cross sections. The values of GLK for cross-dating of decay classes 2 and 3 (Table 3) were both highly significant ( $p < 0.001$ ) for 33% of the stumps dated. The values of GLK were high in all cross sections (never <60%). However, when the stumps grouped in decay classes were compared with the number of years since tree death, variance of the data sets was found to be high (Fig. 3). For *Fagus sylvatica*, class 1 died from 2002 to 1977, class 2 died from 1996 to 1959, and class 3 died from 1994 to 1947; for *A. alba*, class 1 died from 2002 to 1976, class 2 died from 1998 to 1962, and class 3 died from 1987 to 1951 (Fig. 3).

Comparing the mean values of years since tree death for each class with a Student's *t* test, significant differences appeared ( $p < 0.01$ ) among classes of the two species, except between the second and the third class of *A. alba* (Fig. 3). Mean time since tree death for *Fagus sylvatica* trees was 17 years for the first class, 29 years for the second class, and 40 years for the third class. For *Abies alba*, years since death were 17, 26, and 32 for the first, second, and third decay classes, respectively (Fig. 3).

Comparing the decay rates of the two species highlighted how *F. sylvatica* and *A. alba* tend to decompose at the same rate (Figs. 4a and 5a) with the exception of the third class, for which a statistical difference was found (Student's *t* test,  $p < 0.01$ ). *Fagus sylvatica* needed more time to pass from the second to the third class than *A. alba*. However, Table 2 (*A. alba*) and Table 3 (*F. sylvatica*) also showed that there is a continuum of tree death and a difference in the transition rate from one class to another in the different samples.

### Tree-ring patterns and tree life history prior to death

Mean ring-width chronologies of all stumps, grouped in the three decay classes, were compared statistically with the main chronology of living trees for each site.

At the *F. sylvatica* site (Fig. 4a), the ring-width curve of all stumps showed highly significant correlations with their

Fig. 2. Mean chronology and number of cores (□) at the *Fagus sylvatica* (broken lines) and *Abies alba* (solid lines) sites.

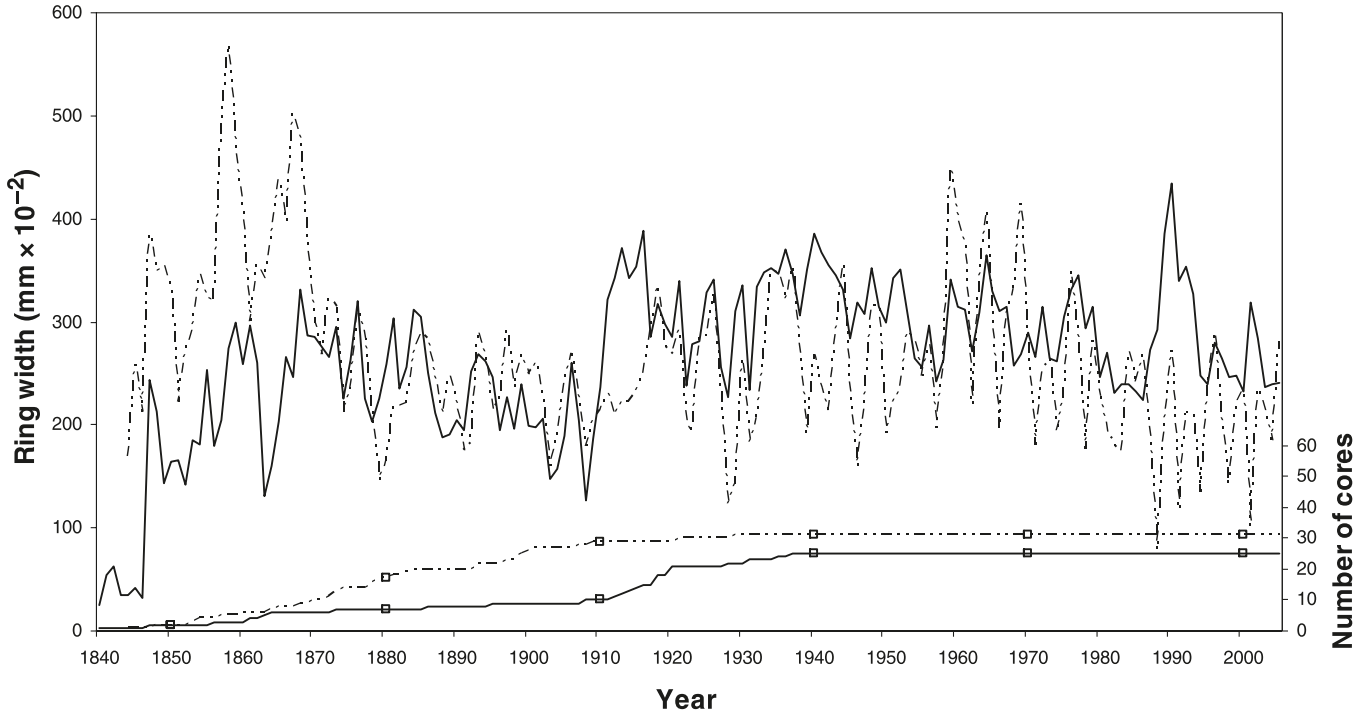
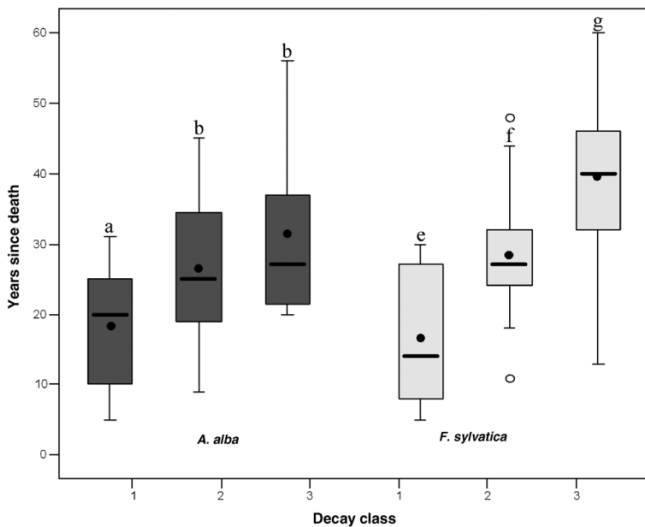


Fig. 3. Number of years since death for dated stumps, according to their decay classes at the *Abies alba* site (heavily shaded boxes) and at the *Fagus sylvatica* site (lightly shaded boxes), represented as box-plot distributions. In the box plot, the upper limit corresponds to the value of the first quartile (Q1) of the distribution and the lower limit to the third quartile (Q3); the solid circle shows the mean, and the heavy horizontal line is the median. The error bars connect the two extreme values, obtained as a linear combination of the Q1 and Q3 values. Cases with values more than three box lengths from the upper or lower edge of the box are shown as open circles. Boxes with different letters within the species indicate highly significant differences in years since tree death.



living-tree reference curve. The GLK values were highly significant ( $p < 0.001$ ) for all decay classes, with values  $>74\%$ , whereas the TVBP was generally  $>7.3$ . The three curves matched each other well, showing a good synchronic-

ity of negative (e.g., 1878, 1891, 1928, 1939, 1946, 1957, 1960, 1962, and 1966) and positive peaks (e.g., 1858, 1926, 1944, 1959, and 1964) with the living-tree main chronology. The chronology built with stumps of decay class 1 extended from 1810 to 2002, and decay class 3 covered the interval from 1828 to 1994.

The chronology of stumps of decay class 2 was the oldest observed, with a time interval extending from 1718 to 1996. This curve showed a gradual growth reduction from 1720 to 1757 and a very slow growth for the subsequent 60 years, but caution is needed in the interpretation of growth trends based on a single stump. After that, there was an evident growth release. Synchronously with this trend, other trees established in the following years. These were classified into different decay classes, which can be clearly observed in Fig. 4b. In fact, after 1838, the number of the dead cross sections sampled and dated increased dramatically. Each ring-width series of cross sections showed a plateau (Fig. 4b), which was rather similar in the different classes. These plateaus corresponded with the period from 1920 to 1970 when there were a maximum number of trees in the studied area. In these years, there was also the maximum synchronicity of negative and positive peaks between the curve of trees prior to death and the main chronology for living trees.

At the *A. alba* site (Fig. 5a), the ring-width curve of stumps showed significant correlations with their living-tree reference curve. The GLK values were always highly significant ( $p < 0.001$ ), with values of 75%, whereas the TVBP was always  $>4$ . The chronology of decay class 1 extended from 1870 to 2001. The chronology of stumps of decay class 2, the oldest one, covered the interval from 1793 to 1998, and the decay class 3 chronology extended from 1872 to 1987. Even in this case, curves showed a consistent synchronous occurrence of negative peaks (e.g., 1908, 1922,

**Table 2.** Year of tree death at the *Abies alba* site and statistics of cross-dating with the mean chronology of the living trees.

Sample	Decay level	Year of death	GLK	GSL	TVBP
a8_1d	1	2002	64	**	3.9
a3_1d	1	2002	69	***	4.2
a10_1d	1	2001	68	***	4.2
a12_1d	1	1999	63	**	3.6
a8_2d	2	1998	68	***	4.0
a5_1d	1	1997	69	***	2.0
a21_2d	2	1995	65	**	3.5
a9_2d	2	1994	80	***	6.5
a3_2d	2	1993	70	***	4.5
a11_2d	2	1993	68	***	3.7
a1_1d	1	1992	70	***	5.6
a14_2d	2	1989	65	**	3.6
a14_1d	1	1989	66	**	5.0
a9_1d	1	1988	65	**	1.8
a4_1d	1	1987	68	***	2.9
a19_2d	2	1987	66	**	3.4
a3_3d	3	1987	79	***	7.0
a7_3d	3	1987	71	***	4.6
a7_2d	2	1987	71	***	5.0
a18_1d	1	1986	73	***	2.7
a6_3d	3	1986	67	***	1.6
a16_1d	1	1985	68	**	2.0
a9_3d	3	1985	67	**	5.5
a24_2d	2	1984	74	***	3.8
a2_3d	3	1984	64	**	2.8
a4_3d	3	1984	64	**	4.4
a2_1d	1	1983	67	***	4.0
a23_2d	2	1982	73	***	3.6
a18_2d	2	1982	73	***	6.5
a11_1d	1	1982	72	***	1.4
a1_2d	2	1982	71	***	3.1
a17_1d	1	1982	65	**	2.7
a13_1d	1	1981	69	***	2.9
a15_1d	1	1981	68	***	2.6
a2_2d	2	1979	67	***	2.0
a7_1d	1	1976	62	**	2.5
a5_3d	3	1976	72	***	7.2
a22_2d	2	1976	68	**	2.9
a12_2d	2	1975	63	*	3.0
a11_3d	3	1974	64	**	2.6
a20_2d	2	1974	68	**	3.1
a13_2d	2	1974	65	**	2.5
a8_3d	3	1972	64	**	3.7
a5_2d	2	1971	75	**	2.2
a6_2d	2	1971	68	**	2.2
a15_2d	2	1969	76	***	1.7
a10_3d	3	1968	70	**	2.3
a17_2d	2	1965	80	***	0.9
a16_2d	2	1964	68	**	1.9
a10_2d	2	1962	66	**	3.2
a1_3d	3	1955	66	**	2.8
a12_3d	3	1951	88	***	2.2

**Note:** Samples are listed in chronological order and related to the class of decay. A gray scale is used to stress the continuum through decay levels. GLK, percent agreement in the signs of the first differences of the two time series (the Gleichlaufigkeit); GSL, statistical significance of the GLK: \*\*\*99.9%, \*\*99%, \*95%; TVBP, Student's *t* value modified by Baillie and Pilcher (1973) and Munro (1984).

1928, 1931, and 1935) and positive peaks (e.g., 1906, 1934, 1940, 1952, and 1959) with the living-tree main chronology, as well as with each other. They also revealed common growth trends, for example, from 1934 to 1940 and from

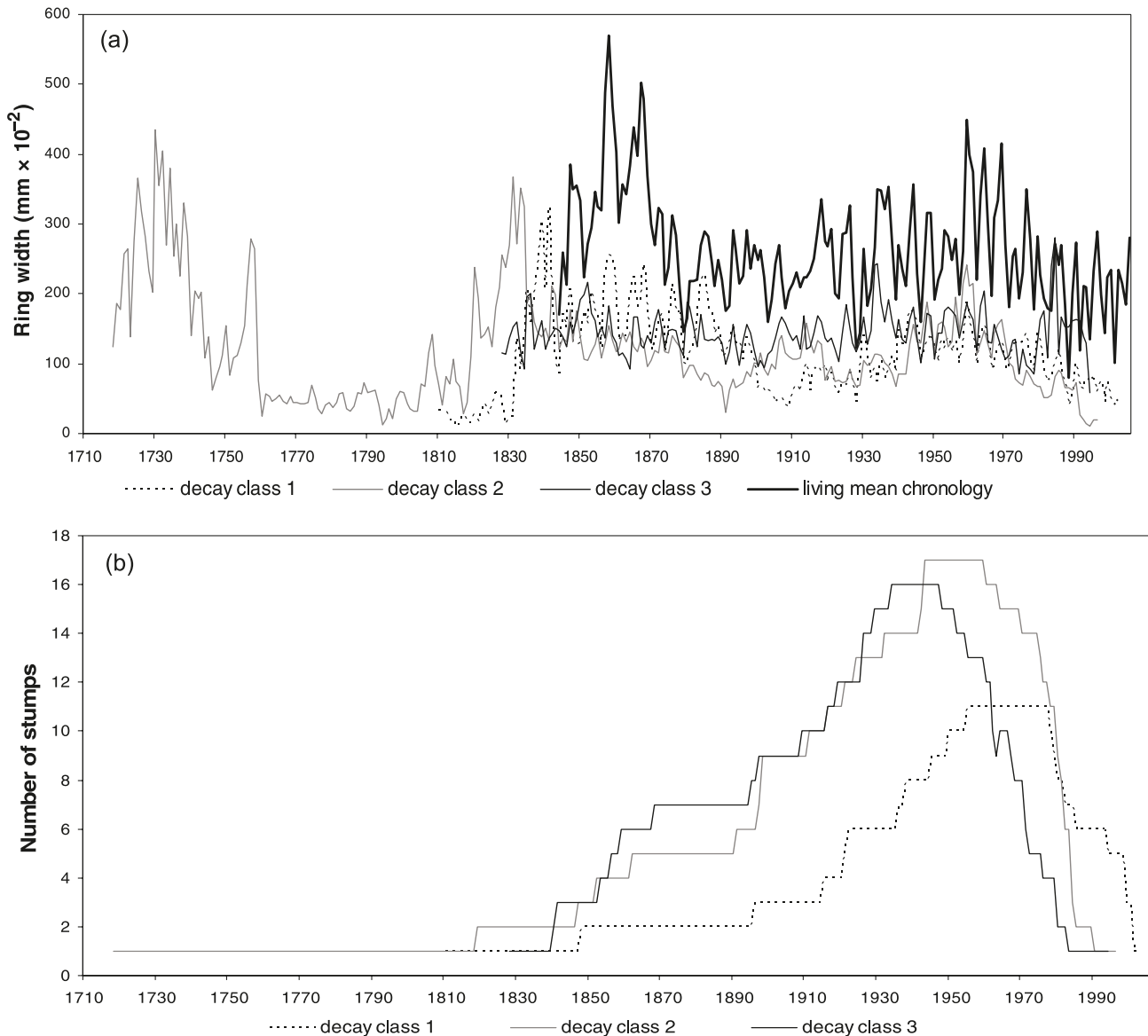
**Table 3.** Year of tree death at the *Fagus sylvatica* site and statistics of cross-dating with living tree mean chronology.

Sample	Decay level	Year of death	GLK	GSL	TVBP
f5_1d	1	2002	68	***	6.6
f6_1d	1	2000	68	**	3.2
f7_1d	1	2000	62	*	3.6
f1_1d	1	1998	69	**	3.9
f11_1d	1	1998	73	***	4.0
f13_2d	2	1996	66	**	4.6
f4_3d	3	1994	81	***	2.7
f9_1d	1	1993	63	***	3.9
f3_2d	2	1989	63	***	3.9
f2_1d	1	1984	69	**	4.0
f9_2d	2	1984	61	**	2.9
f4_2d	2	1983	76	***	1.8
f12_2d	2	1983	60	*	3.2
f14_2d	2	1983	72	***	2.6
f12_3d	3	1982	61	**	3.5
f8_1d	1	1981	90	***	2.9
f1_2d	2	1981	74	**	1.9
f16_2d	2	1981	70	**	2.6
f10_2d	2	1980	64	**	3.9
f3_1d	1	1979	63	*	4.5
f2_2d	2	1979	62	**	2.5
f6_2d	2	1979	68	**	2.7
f1_3d	3	1979	66	**	5.8
f13_3d	3	1979	68	***	5.1
f10_1d	1	1978	69	***	2.7
f4_1d	1	1977	66	**	2.4
f5_2d	2	1977	71	***	2.5
f8_2d	2	1975	62	**	3.8
f11_3d	3	1975	61	**	2.7
f11_2d	2	1974	63	**	3.7
f17_3d	3	1971	65	***	2.7
f6_3d	3	1970	71	**	2.6
f15_3d	3	1970	60	*	4.6
f7_2d	2	1969	69	***	2.9
f10_3d	3	1967	76	***	2.5
f14_3d	3	1966	60	*	3.5
f17_2d	2	1963	72	**	2.9
f9_3d	3	1962	70	**	2.0
f2_3d	3	1961	85	***	2.4
f16_3d	3	1961	63	**	2.2
f15_2d	2	1959	66	**	4.4
f3_3d	3	1959	66	**	3.0
f8_3d	3	1954	69	**	3.8
f5_3d	3	1951	68	**	2.9
f7_3d	3	1947	73	**	3.0

**Note:** Samples are listed in chronological order and related to the class of decay. A gray scale is used to stress the continuum through decay levels. GLK, percent agreement in the signs of the first differences of the two time series (the Gleichlaufigkeit); GSL, statistical significance of the GLK: \*\*\*99.9%, \*\*99%, \*95%; TVBP, Student's *t* value modified by Baillie and Pilcher (1973) and Munro (1984).

1951 to 1959. After 1908, living trees had a growth release, whereas stumps did not show such a strong release. Every series of cross sections had a plateau (Fig. 5b), similar to that found for *F. sylvatica*, once more with correspondence between the different classes. The best synchronicity and common growth trend was observed between 1935 and 1975.

**Fig. 4.** (a) Tree-ring chronologies of decay classes and the mean chronology for living trees at the *Fagus sylvatica* site. (b) Number of dead cross sections dated in each class from the *F. sylvatica* site.



The growth rate of stumps prior to death was always lower than that of the corresponding living trees (Figs. 4a and 5a). They reflected a gradual growth reduction before death, starting in 1955 for *F. sylvatica* (Fig. 4a) and in 1950 for *A. alba* (Fig. 5a).

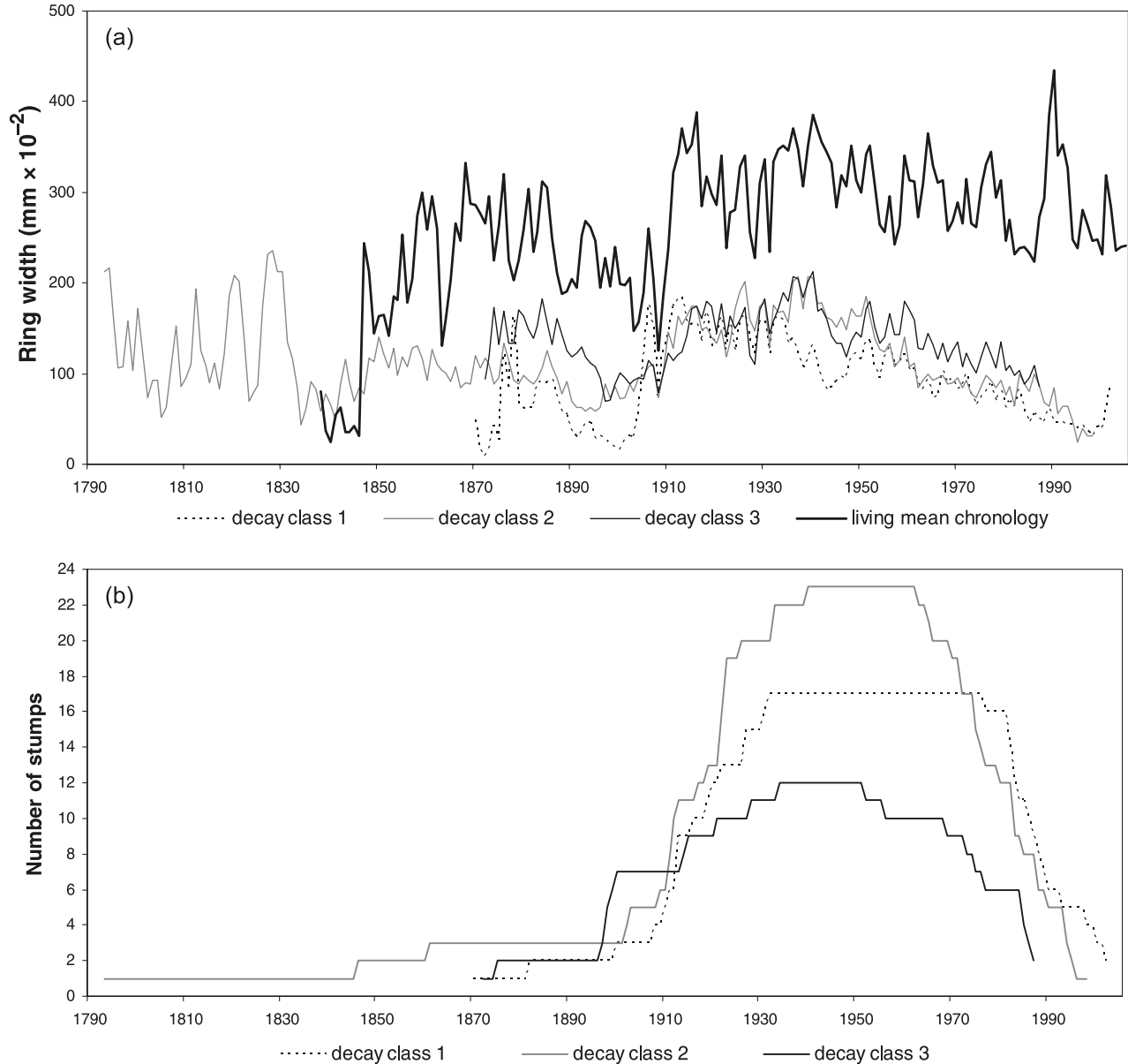
## Discussion

At both the study sites, we found no living trees older than 165 years. This is not surprising because the area was strongly impacted around 1840 by human activities, such as logging for timber and coke production (mainly from coppice beech), fire (particularly in “Abeti Soprani”), and grazing (Di Martino 1988). After the mid-19th century, the number of sampled and dated stumps dramatically increased, showing germination and establishment of a new cohort of trees. If we had only studied living trees, we would not have observed this phenomenon, because the *F. sylvatica*

living-tree chronology started in 1840. The study of dead-wood chronologies along with those of living trees has proved useful for building long tree-ring growth time series to determine historic patterns of tree mortality and understand the structural development of forest stands.

The tree ring widths of *F. sylvatica* varied more annually than those of *A. alba*, and the growth rates were lower in *F. sylvatica* than in *A. alba*. *Fagus sylvatica* is relatively drought resistant compared with other beech species (Fang and Lechowicz 2006). Warmth during the growing season is important for its distribution, because beech is strongly influenced by summer low temperatures that often occur at these sites. *Abies alba* is rather sensitive to increasing temperatures during summer drought (Robakowski et al. 2002), which are rare at the upper altitudes in the central Apennines (Romagnoli and Schirone 1992). Growth reductions in “Abeti Soprani” after 1940 appear to related to increases in summer drought and temperature (Schirone et al. 1993).

**Fig. 5.** (a) Tree-ring chronologies of decay classes and the mean chronology for living trees at the *Abies alba* site. (b) Number of dead cross sections dated in each class from the *A. alba* site.



*Abies alba* has a very high water consumption and seems to be located mainly in humid or even very humid bioclimates (Aussenac 2002).

The two site chronologies revealed similar growth trends only after the 1870. Probably, in the juvenile stage, local environmental conditions along with strong competition processes contributed to varying the growth patterns at the two sites. The annual growth rates of young *F. sylvatica* were higher than those for *A. alba*, probably because of their different shade tolerances (Pagès et al. 2003). Changes in species-specific shade tolerance and light requirements with age may have contributed to the differences between *A. alba* and *F. sylvatica* in surviving under an established canopy. An important role was probably played by climatic variables when the impact of local disturbances disappeared. In fact, similar climatic drivers characterize these sites because they have similar slope and exposure. Even though the two sites

are located at different altitudes, the annual trends in temperature and precipitation are similar at both sites (Romagnoli and Schirone 1992).

Several studies have questioned the suitability of dead-wood decay classification systems in determining the time since death of trees in temperate and boreal regions (Mast and Veblen 1994; Rouvinen 2002). For *Thuja plicata* Donn ex D. Don snags, Daniels et al. (1997) found poor correlations between decay classes and time since death. By contrast, other authors have found that decay classes correspond with time since death quite well (Hennon et al. 1990; Huggard 1999). Huggard (1999) found that the time since death of *Abies lasiocarpa* (Hook.) snags generally increased with decay classes, based on structural characteristics and dated using dendrochronological methods. In our study, significant correlation coefficients with reference chronologies were found for curves of single stumps and a

year of death was assigned to 99 sampled stumps (73% of all stumps sampled). In general, chronologies had synchronous pointer years, i.e. years during which tree rings particularly narrow or wide as a result of extreme climatic events or site-specific conditions are formed. This synchronicity indicates that tree rings were dated correctly and the presence of a site-dependent signal. These results support previous suggestions that dendrochronological methods are useful for estimating tree mortality (e.g., Dynesius and Jonsson 1991; Mast and Veblen 1994; Cherubini et al. 2002). However, the cross-dated year of the last tree-ring in a sample may fail to match the exact year of death of the tree (Cherubini et al. 2002; Storaunet 2004). This could be due to the decay of outer tree rings or to the presence of discontinuous and missing rings, which both occur frequently in suppressed trees and in trees living under conditions of stress (Kramer and Kozłowski 1979). At our sites, wood decay generally proceeded from the pith toward the bark, rather than in the opposite direction, which facilitated dendrochronological dating of stumps. Assigning a calendar year of death to trees is possible only when the outer rings have not decayed or eroded and the sampled portion of the stump includes the last living stem tissue (Dynesius and Jonsson 1991; Daniels et al. 1997).

The correlation between decay classes and the number of years since tree death was not strong, and the age variation of stumps within decay classes was rather high. Nevertheless, the mean age of stumps across decay classes revealed that the stumps had remained relatively fresh without decaying for a period of approximately 20 years following the death of the trees. Overall, cross sections of stumps in the first decay class did not differ from those of living trees; the wood was compacted, and the decay process was apparent in only small portions. Stumps in the second class were clearly decaying: the surface was partly eroded, and decay processes had begun to affect the central portion of the stump. In the third class, cross sections had become softer, and the soft outer layers disintegrated easily.

Climate probably plays an important role in influencing decay rates. Our stumps tended to decompose faster than other dead wood components and faster than stumps in studies conducted in colder areas of central and northern Europe (Storaunet and Rolstad 2002; Zielonka 2006). It must be pointed out that our tree ring data provide information on the year of tree death, whereas no insight is given on the time spent by the tree as a snag before falling on the forest floor, where decaying processes are rapid.

Within the same species, significant differences in the year of tree death among classes were observed. Comparing the mean years since tree death for each class with such a high variance may be considered a statistical artifact, without much biological significance. We found only a rough correlation between the stage of decay and the time since death of stumps. Because of the wide range in the time since death, the mean value provided little information relevant to determining the rate of change and only a rough way to describe the time of transition from one class to another. If more samples were collected in these forest stands, it should be possible to adjust the overlaps between classes more finely. Trees died and decayed on a continuum, which makes it impossible to group and compare the year of death

with the class of decay. The structural condition and age distribution of the wood at the time of tree death may have influenced how the stumps were classified into decay classes. This affects estimates of the rate of decay and of time needed to pass from one decay class to the next (Sollins 1982).

When studying the stumps of trees that had died naturally, additional information is required to discern if the decay is the effect or the cause of the death. In fact, the agent of tree mortality might influence considerably the decaying processes to which wood is exposed, as Zielonka (2006) observed in old-growth spruce forests in Poland. The continuum observed in the year of tree death through decay levels (grayscale in Tables 2 and 3) revealed, in particular, the correlation between year of death and decay classes was more irregular in *A. alba* than in *F. sylvatica*. One reason for this could be that *A. alba* trees had a tendency to die standing more frequently than *F. sylvatica* trees (Zielonka 2006). Therefore, *A. alba* stumps were less exposed to decaying processes than *F. sylvatica*. The prevalence of standing deadwood at the *A. alba* site, probably as a result of suppression, would imply that deadwood in the early stages of decomposition more frequently occurred as snags rather than woody debris. Conversely, the predominance of falling trees resulting in mortality at the *F. sylvatica* site, possibly because of windstorms, would cause a more common incidence of woody debris in the early phases of deadwood decay. Unfortunately, we were unable to identify whether these stumps from trees that had died naturally were the result of sudden breaks or from trees that had died years before falling down. For this reason, decay classes with advanced states of decomposition included several stumps younger than the mean of that class. This might imply that these trees had suffered from progressive weakening of the bole through fungal decomposition or natural hazards while still alive. Presumably, these trees started to decompose in some portions of their wood before dying and, therefore, decayed faster than uncontaminated wood after death. To understand the relationship between the year of death and the class of decay better, the cause of death of each tree should be known. For example, in a tree killed by insects, the main part of the wood may remain fresh and solid for a long time, and the tree may stay standing for many years before falling. On the other hand, a tree covered with rot fungi could fall down only a few years after its death (Storaunet and Rolstad 2002) and be subject to a much faster rate of decay.

The year of formation of the outermost tree ring in stump cross sections has always been considered the year of death. However, the year of cessation of cambial activity is not necessarily the year of death, because green needles may continue living for some years after the cambium has ceased functioning even if no new wood cells are formed (Mast and Veblen 1994). Both *F. sylvatica* and *A. alba* seem to decompose at the same rate; significant differences were only seen for the third class. In the latter case, *F. sylvatica* decomposed more slowly than *A. alba*. After the same number of years (e.g., 32), *A. alba* stumps showed characteristics of the third class, whereas *F. sylvatica* typically still belonged to the second. Nonetheless, death and decay classes were inconsistent among the trees, and the structural characteristics

of stumps did not always reflect the length of time they had been dead (see Daniels et al. 1997). Several stumps may have died and continued decaying for many years, but the last living section of the stem may have stopped functioning rather recently (Cherubini et al. 2002). Therefore, some features of a stump could erroneously indicate advanced stages of decay and mask a recent tree death. Thus, the study of decay classes and the visual classification of stumps was not a useful way of calculating the rate of change, because the stage of decay did not relate to the time since death determined by dendrochronological methods. The broad diameter range of stumps sampled may have also contributed to the discrepancy observed in the year of death for stumps of the same class. Trees with a larger diameter decomposed more slowly than smaller ones (Frangi et al. 1997), which explains why decay classes based on trunk deterioration appeared to be less precise in estimating the time since death of trees.

In general, stumps showed a slowly decreasing growth trend prior to tree death, which is commonly used as an indicator of declining tree vitality; in turn, the slower growth is often associated with the beginning of death processes (Waring 1987; Cherubini et al. 2002; Bigler et al. 2004). The process of dying often takes decades (Kaufmann 1996; Villalba and Veblen 1998) and is driven by a sequence of multiple stress factors (Manion 1981; Houston 1984). At the sites in this study, the stumps showed a more pronounced decline in growth trends than living trees, which can be related to long-term stress caused by a reduced availability of resources (light, nutrients, etc.) or increasing competition. Mortality is a highly variable and unpredictable event in forest stands (Franklin et al. 1987). Periods with unusually low or high mortality may occasionally occur, leading to local breaks or peaks in the temporal continuity of deadwood in the earliest decay class. Highly decayed deadwood may be present over a period of several decades and, therefore, can be expected to vary less than in the earlier decay classes (Vanderwel et al. 2006).

The relatively long persistence of stumps in the forests we studied illustrates how difficult it is to use categorical decay indexes based on visual assessments of structural decay and highlights the importance of timing deadwood decomposition in mortality models. Although stumps are useful in estimating the year of tree death, assessing downed trees is even more helpful understanding deadwood temporal dynamics. We need to know more about these dynamics to sustain deadwood-dependent organisms (Grove 2002). Downed trees usually contribute the largest volume of biomass in forest ecosystems and decompose differently from stumps (McComb and Lindenmayer 1999). Accurate estimates of the temporal dynamics of deadwood would be useful to parameterize decay models aimed at analyzing the carbon balance of forest stands. The resulting decay models could help to determine the carbon sequestration potentials in a particular region and, thus, help to set realistic goals for tackling global warming. Better estimates would also help to describe the succession of populations in the deadwood habitat and contribute to a better understanding of the evolution of compositional, structural, and functional diversity of forest canopies.

In conclusion, existing decay classification schemes were

not appropriate for these forest stands, although they may still be useful to qualitatively describe deadwood decomposition processes. Indeed, the linkage between time since death and decay classes was not rigorous, and a continuum through deadwood decomposition levels occurred that showed a high variability in the transition rate from one decay class to the next, which complicates the picture of the decay process.

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