

Temporal dynamics of instream wood in headwater streams draining mixed Carpathian forests



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ARTICLE INFO

Keywords:

Instream wood
Wood residence time
Cross-dating
Headwater stream

ABSTRACT

Instream wood can reside in fluvial systems over varying periods depending on its geographical context, instream position, tree species, piece size, and fluvial environment. In this paper, we investigate the residence time of two typical species representing a majority of instream wood in steep headwaters of the Carpathians and located under mixed forest canopy. Residence times of individual logs were then confronted with other wood parameters (i.e., wood dimensions, mean annual increment rate, tree age, class of wood stabilisation and decay, geomorphic function of wood pieces, and the proportion of the log length within the active channel). Norway spruce (*Picea abies* (L.) Karst.) samples indicated more than two times longer mean and maximal residence times as compared to European beech (*Fagus sylvatica* L.) based on the successful cross-dating of 127 logs. Maximum residence time in the headwaters was 128 years for *P. abies* and 59 years for *F. sylvatica*. We demonstrate that log age and log diameter played an important role in the preservation of wood in the fluvial system, especially in the case of *F. sylvatica* instream wood. By contrast, we did not observe any significant trends between wood residence time and total wood length. Instream wood with geomorphic functions (i.e., formation of steps and jams) did not show any differences in residence time as compared to nonfunctional wood. Nevertheless, we found shorter residence times for hillslope-stabilised pieces when compared to pieces located entirely in the channel (either unattached or stabilised by other wood or bed sediments). We also observed changes of instream wood orientation with respect to wood residence time. This suggests some movement of instream wood (i.e., its turning or short-distance transport), including pieces longer than channel width in the steep headwaters studied here ($1.5 \leq W \leq 3.5$ m), over the past few decades.

1. Introduction

Instream wood is a key element in many river systems, as it is interacting with channel and floodplain geomorphology, hydrology, and ecology in many different ways. Instream wood thereby influences channel morphology and geomorphic processes (Montgomery et al., 2003; Gurnell, 2013; Le Lay et al., 2013), or enhances instream (Wohl and Scott, 2017) and floodplain inorganic sediment deposition (Wohl, 2013). Moreover, instream wood accumulations increase frictional resistance to flow (Shields and Gippel, 1995; Curran and Wohl, 2003; Mutz, 2003; Wilcox et al., 2011) and therefore slow down the passage of flood waves or modify flow hydrographs in small streams (Gippel et al., 1996; Davidson and Eaton, 2013; Wenzel et al., 2014) in a way that promotes overbank flow (Triska, 1984; Brummer et al., 2006). In general terms, these physical impacts of instream wood tend to improve habitats for some invertebrates and fish species (Harmon et al., 1986;

Nagayama et al., 2012; Pollock and Beechie, 2014) and to increase the retention of nutrients (Smock et al., 1989) and organic material (Bilby and Likens, 1980).

Instream wood usually has a rather limited residence time in fluvial environments. This time is often referred to as the time which a wood piece spends in the channel between its recruitment to the channel (e.g., by windthrow, landslide, or bank erosion) to its removal from the channel reach through decay (by physical and chemical weathering or biological decomposition), downstream transport, or burial in floodplain sediments (Gurnell et al., 2002; Ruiz-Villanueva et al., 2016; Wohl, 2017). Residence time can be approximated by ¹⁴C radiocarbon dating for older (i.e., at least several hundred old) wood pieces or by cross-dating of instream wood with living material if the first is well-preserved and/or shows clear tree-ring structures (Hyatt and Naiman, 2001; Stoffel et al., 2010). The latter approach allows determination of the year of tree death, which, however, does not necessarily correspond

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Table 1
Characteristics of studied streams and large wood (LW) and small wood (SW) deposition in the streams.^a

Stream	L (km)	A (km ²)	S (m/m)	W (m)	Dec%	n LW (per 100 m)	Vol LW (m ³ ha ⁻¹)	n SW (per 100 m)	Vol SW (m ³ ha ⁻¹)
Mazák 1	0.52	0.13–0.40	0.13–0.25	2.3–3.2	45	48.6	210	27.2	8
Mazák 2	0.25	0.06–0.10	0.19–0.26	1.5–2.4	85	39.2	95	64.4	17
Mazák 3	0.30	0.08–0.13	0.21–0.37	2.3–3.6	95	30	26	66.3	16

^a L – stream length, A – basin area, S – channel slope; W – active channel width, Dec – mean proportion of deciduous tree canopy within the valley corridor (± 30 m from the channel banks), n LW – number of LW pieces per 100 m channel length, Vol LW – volume of LW pieces per channel area, n SW – number of SW pieces per 100 m length, Vol SW – volume of SW pieces per channel area.

with the exact year of entrance of a particular wood piece into the fluvial system. However, in mountain headwaters, adjacent valley slopes are usually very steep and instream wood tends to be recruited close to the channel, such that storage of wood on the slopes above the channel for extended times is rather unlikely (Jochner et al., 2015).

Turnover time of instream wood depends on many internal and external factors and generally ranges from a few years to several centuries. Instream wood in the humid tropical zone tends to decompose much faster as compared to instream wood in dry and/or cold climatic zones (Wohl, 2013). For example, Wohl et al. (2009) documented frequent removal of logjams by chemical weathering and frequent flash floods in a tropical stream in Panama during a 2-year survey, whereas residence times of hundred years are very common in streams draining conifer boreal forests in Scandinavia (Dahlström et al., 2005) or the Pacific Northwest of the U.S. (Hyatt and Naiman, 2001). In case of completely buried wood in floodplain sediments, wood residence time can be increased up to thousands of years because the material will be conserved under anaerobic conditions (Bilby et al., 1999; Wohl, 2013). Instream wood decay rates also depend on tree species, whereby conifers tend to be preserved for longer periods of time as compared to deciduous species (Díez et al., 2002; Dahlström et al., 2005; Ruiz-Villanueva et al., 2016). In addition, other environmental factors, such as the repetition of drying-wetting cycles or water chemistry will affect instream wood residence time as well (Bilby et al., 1999; Díez et al., 2002; Wohl, 2013). Moreover, Spänhoff and Meyer (2004) documented that the microbiological decomposition of individual logs with relatively large dimension is slower than that of smaller wood pieces, owing to a higher surface area-to-volume ratio of larger pieces when compared to smaller ones. Finally, rivers with channel widths exceeding riparian tree height are also able to transport all wood pieces downstream and potentially out of the reach, whereas the mobility of instream wood in narrower channels is assumed to be much more limited (Gurnell et al., 2002; Hassan et al., 2005; Jones et al., 2011; Wyzga et al., 2015).

Wood decomposition rate (often expressed with the decay or depletion coefficient k) is used as a proxy for instream wood residence time in fluvial systems. It takes the form of a negative exponential function:

$$M_f = M_i \cdot e^{(k \cdot t)} \quad (1)$$

where M_i is the initial amount of wood in a fluvial system (represented by wood mass, volume, or number of pieces), and M_f is the quantity of wood left at time t (Ruiz-Villanueva et al., 2016). The decay coefficient k in fluvial environments usually varies between 0.01 and 3.10 per year; however, this variation is highly dependent on tree species, wood chemistry, piece size, and stream environment (Díez et al., 2002; Scherer, 2004; Janisch et al., 2005; Wohl, 2017).

Therefore, the aim of the study is to assess the residence time of instream wood in headwater streams of the western Carpathians and to determine all those wood parameters that affect depletion rates of instream wood in the study areas. We investigate two locally dominant tree species providing instream wood, namely European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) Karst.). Cross-dating was applied to obtain the exact year of tree death and, thus, the year of

potential wood recruitment into the channels. Additional instream wood parameters (i.e., wood dimensions, mean annual increment rate, tree age, class of wood stabilisation, class of wood decay, proportion of log length within the active channel and geomorphic function of wood) were investigated to assess their potential relation with wood residence times. Instream wood mobility in the studied headwaters was indirectly evaluated via the plotting of wood residence time (i) by changes in wood orientation against flow direction and (ii) by wood incorporation into jams. We assume that pieces with longer residence times will have their orientation parallel to the flow direction and that they will be aggregated in log jams as the consequence of their fluvial transport.

2. Studied streams

Three steep headwater channels (Mazák 1, Mazák 2, and Mazák 3; Table 1) were examined in this study; they are situated on the south-facing slope of Mt. Lysá hora (1323 m asl), the highest peak of the flysch Outer Western Carpathians in the Czech Republic (Fig. 1). The study site is one of the most humid locations in central Europe, with mean annual precipitation totals at Lysá hora Mt. amounting to 1390 mm on average during the standard 1961–1990 period and ranging from 1090 mm (1990) to 1896 mm (1966) (Šilhán et al., 2013). The region is formed predominantly by thick-bedded flysch containing sandstones and shales of Late Cretaceous age, which have later been shaped into a monoclinally arranged nappe (Silesian unit) (Menčík et al., 1983). Flysch lithologies are famous for the frequent occurrence of slope instabilities, and landslides are indeed also frequent at our study sites (Pánek et al., 2011a, 2011b; Šilhán et al., 2013). As a result, relatively fine particles with a low proportion of boulder fractions are repeatedly delivered into the local channels (Galia et al., 2015). In addition to fluvial transport during flood events, wood and sediment are also mobilized by occasional, small-magnitude debris flows in the steepest valleys and local channels (Šilhán, 2014; Tichavský et al., 2014; Šilhán et al., in review).

All streams analysed here are located in the Nature Reserve Mazácký Grúnik, an area which has been created to preserve nature and therefore also to prevent the removal of instream wood by local residents. This protection status is essential for the purpose of our assessment as wood removal is a common practice in other steep mountain channels of the Czech Carpathians (Galia and Hradecký, 2014). Forests cover 99.6% of the nature reserve and consist mainly of European beech (*F. sylvatica*; 62%) and Norway spruce (*P. abies*; 31%). In addition, Sycamore maple (*Acer pseudoplatanus* L.) and Silver fir (*Abies alba* Mill.) occur occasionally (both with $\leq 2\%$ representation). Typical tree ages range between 60 and 100 years, but much older trees (up to 170 years old) have been reported to grow in the valley corridor of Mazák 1 (www.geoportal.lesy.cz).

The presence of instream wood in the channels is controlled by mortality of individual trees on the steep, adjacent hillslopes. In addition, and based on field observations, snowloading, windstorms, and rainfall-induced waterlogging of hillslopes can be perceived as additional, yet important wood recruitment agents as well. On the other hand, bank erosion is practically negligible owing to high channel confinement. Instream wood abundance differs between the individual

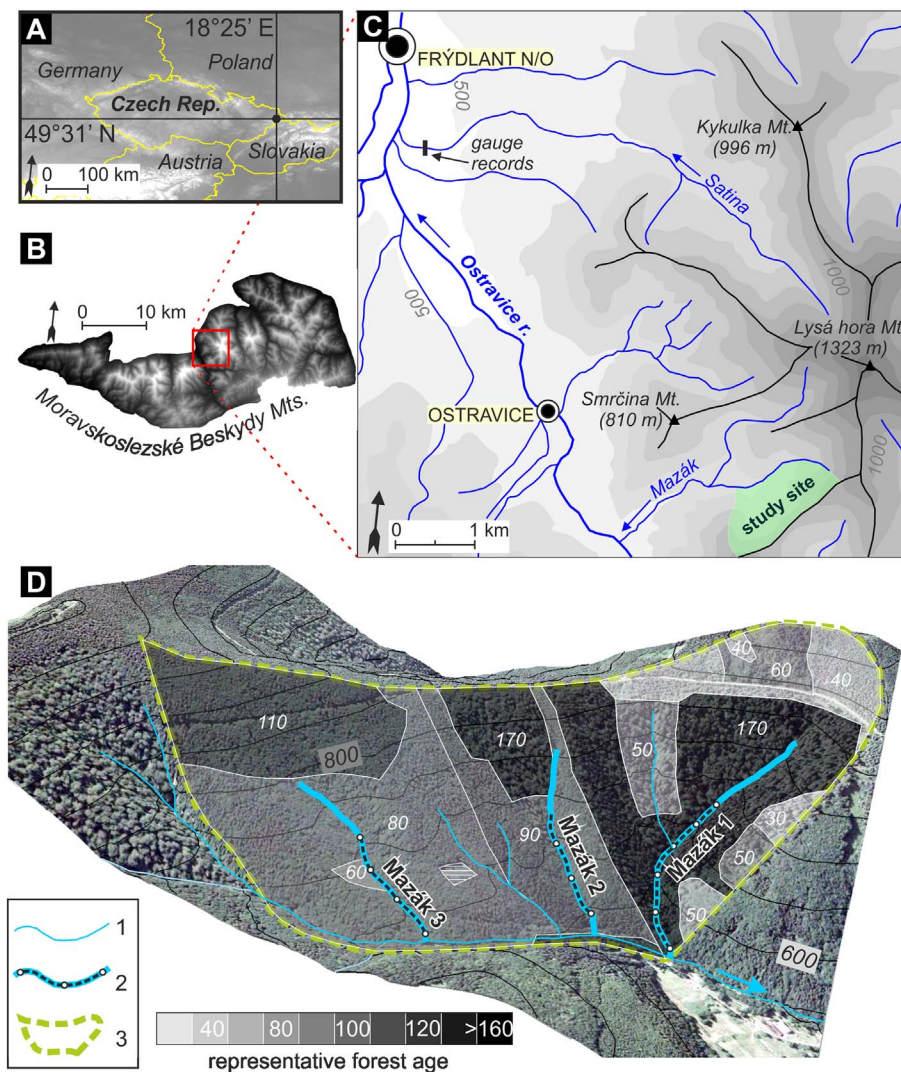


Fig. 1. Geographical position of studied streams at different scales (A–D). 1 – Watercourses, 2 – studied streams, 2 – boundary of the Nature Reserve Mazáký Grúnik.

channels (Table 1). Mean large wood (LW) volumes per channel area, including all pieces corresponding to commonly accepted LW metrics (i.e., length ≥ 1 m, diameter ≥ 0.1 m sensu Wohl et al., 2010), vary from $26 \text{ m}^3 \text{ ha}^{-1}$ in Mazák 3 to $210 \text{ m}^3 \text{ ha}^{-1}$ in Mazák 1, with frequencies of 30–48.6 pieces per 100 m channel length. Small wood (SW; with a length ≥ 1 m and diameter ≥ 0.05 m or a length ≥ 0.5 m and diameter ≥ 0.1 m) plays an important role in these catchments, especially in those channel reaches where *F. sylvatica* represents a major proportion of forest canopy in the valley corridor, therefore resulting in the occurrence of up to 66 small wood pieces per 100 m channel length and mean volumes of up to $16.8 \text{ m}^3 \text{ ha}^{-1}$ per channel area (Galia et al., submitted).

3. Methods

3.1. Instream wood dating

Analyses focused on the two main tree species occurring in the channels, namely *F. sylvatica* and *P. abies*. The dominant tree species with 153 log pieces was *F. sylvatica*, as compared to 36 pieces of *P. abies*. This sample size represented 16% of all LW and SW occurring in the studied channels. The *P. abies* logs were sampled only in Mazák 1 and Mazák 2, whereas *F. sylvatica* came predominantly from Mazák 3. The largest number of logs were sampled in Mazák 1 (81 logs) and the smallest number in Mazák 2 (41 logs).

Dating of outermost rings and inferences to tree death were performed with dendrochronological approaches. All analysed logs were at least partially located in the active channel and selected using the following criteria: (i) the first tree ring below the bark was presented for exact determination of the year of tree death; (ii) the log diameter was larger than 8 cm, which ensured the presence of at least 30–40 tree rings (according to mean tree-ring widths obtained from reference trees), which is considered as a lower threshold for successful dendrochronological dating; and (iii) the physical state of log wood had to be of sufficient quality to enable the extraction of a sample stable enough to allow for tree-ring analysis. Sample extraction was then done in two different ways. From logs with good wood quality, two increment cores (with a diameter of 0.5 cm and a maximum length of 40 cm) were extracted with a Pressler borer from two opposite sides of each log. Logs with lower wood quality (i.e., initial wood decay, insect damage) were sampled by a handsaw; a large wedge reaching the pith was cut in this case. In every case, samples were extracted from those parts of the logs where wood quality was the highest (i.e., often from submerged parts). In many cases, multiple attempts were needed to obtain samples with acceptable wood quality.

In addition, reference chronologies were created using increment cores from 20 undisturbed trees of each species present in the catchment. Preference was given to the trees with the largest stem diameter as they were expected to yield a long series of rings. Two increment cores were taken in this case from two opposite stem sides

and at positions located perpendicular to the slope at the standard breast height of 1.3 m.

All samples were air dried for a few weeks. Increment cores were glued onto woody supports. Wedge cuts and cores were sanded (80, 250, 1000 grit sand papers), tree rings were counted and their widths were measured (0.01 mm precision) under binocular microscope by using the dendrochronological measuring device TimeTable (VIAS, 2005) and the PAST4 software. The reference chronology was created from the increment curves of the reference trees and by using Arstan (Cook, 1983) and a double detrending procedure (Holmes, 1994). In a next step, increment curves from the instream wood were cross-dated against the reference chronology; cross-dating was performed visually (Rybníček et al., 2010) and by using the statistical tests provided by PAST4. The quality of cross-dating was checked by four indicators: (i) the *t*-test following Baillie and Pilcher (1973) (TBP), (ii) the *t*-test following Hollstein (1980) (THO), (iii) the coefficient of agreement (or Gleichläufigkeit (GlF); Eckstein and Bauch, 1969), and (iv) the overlap of the instream wood ring-width data with the reference chronology. The following minimal thresholds were applied for the cross-dating: 3.5 for TBP and THO, 60% for GlF, and 35 tree rings overlapping with the reference chronology. The cross-dating was considered successful as soon as at least three thresholds were met.

3.2. Instream wood parameters

In the field, we also measured the dimensions and additional wood parameters for all pieces selected for dating. We recorded total log length (with an accuracy of ± 0.05 m), the proportion of log length within the active channel ($\pm 5\%$), and the diameters at log ends and above the boundaries with the active channel (± 0.005 m). Total wood volume and in-channel wood volume was then calculated by the truncated cone approximation. We also identified decay classes with a visual approach as follows: 1 – piece with intact bark on $> 50\%$ of the log surface; 2 – piece with no bark or low proportion of bark ($\leq 50\%$), but still with wood remaining hardwood; 3 – with wood being soft as a result of advanced decay.

For the classification of wood stabilisation classes, we used the following criteria: A – unattached wood entirely located in the active channel; B – hillslope-stabilised wood ('ramp' or 'collapsed bridge' sensu Wohl et al., 2010); C – piece stabilised in the active channel by other instream wood or bed sediments. In addition, the orientation of wood in relation to the main flow direction (measured in 22.5° intervals) was recorded in the range of 0–180° (with 0° being parallel and 90° being perpendicular). The observed geomorphic function of instream wood was then divided into two categories: jam formation (≥ 3 pieces in close interaction with each other sensu Wohl and Cadol, 2011) and step formation (step height ≥ 0.3 m).

Exponential wood depletion rate functions were then calculated on the basis of cross-dated instream wood pieces. We used two approaches to obtain depletion rates, i.e., either by (i) plotting the cumulative number of dated *F. sylvatica* and *P. abies* logs and by (ii) assessing the cumulative volume of these logs (both total and in-channel volumes). The resulting relationship has the following form:

$$y = a \cdot e^{(-k \cdot t)} \quad (2)$$

where *y* is the cumulative relative abundance of instream wood pieces (%) or cumulative total or in-channel wood volume (m³), and *t* is the wood residence time in years obtained by cross-dating. The empirical coefficients are represented by *a* and *k*; where *k* is usually expressed as the decay or depletion coefficient (Hyatt and Naiman, 2001; Scherer, 2004; Ruiz-Villanueva et al., 2016).

3.3. Statistical analysis of wood parameters

We then tested relationships between wood residence time, stabilisation and decay classes, and geomorphic functions of wood. The

assumption about normal distribution of the analysed parameters was assessed through the use of standard methods (skewness, kurtosis, and omnibus normality; NCSS, 2016). Because the normality criteria had to be rejected for all data sets, the nonparametric Kruskal-Wallis test was used to test potential differences between the stabilisation and decay classes among all data sets and/or observed tree species. The related post-hoc multiple-comparison test (Fisher's LSD) was subsequently used to distinguish differences between individual groups. In addition, the Mann-Whitney *U* test was applied to compare log parameters that could possibly influence instream wood residence and to compare residence time between jam-incorporated and outside-jam instream wood, as well as to assess differences between decay classes 2 and 3 of *P. abies* acting as instream wood. All tests were performed at a significance level of 0.05.

4. Results

4.1. Sampled logs and their cross-dating parameters

In total, 189 instream wood pieces were sampled including 153 *F. sylvatica* and 36 *P. abies* logs. As a result of advanced decay and related difficulties with increment ring identification, failure to pass the thresholds or the absence of the first ring(s) below the bark, only two-thirds of all logs sampled (i.e., 127 logs; 67.2%) could be successfully crossdated. We were much more successful in cross-dating *P. abies* (80.6%) than *F. sylvatica* (64.1%). Statistical indices of successfully cross-dated logs were almost identical between *F. sylvatica* (with a mean TBP = 3.83, mean THO = 3.70, mean GlF = 69.73, and mean overlap with reference chronology = 43.9 years) and *P. abies* (mean TBP = 3.79, mean THO = 3.64, mean GlF = 69.25, and mean overlap with reference chronology = 56.0 years) samples (Fig. 2). More details regarding the logs sampled, cross-dating statistics as well as the mean values of indices for all samples and all streams, can be found in Table 2.

4.2. Residence time of instream wood and relations with selected log parameters

In general, *P. abies* logs revealed significantly longer ($p < 0.001$) residence time (57.9 years) in the channel as compared to *F. sylvatica* (18.4 years) (Fig. 3). The longest mean residence time was found in Mazák 1 with 21 years in the case of *F. sylvatica* (21.0 years) and 59.9 years for *P. abies*. The longest residence time observed in *P. abies* equalled 128 years (tree death dated to 1887 CE) and 59 years in the case of *F. sylvatica* (tree death in 1956 CE). More details on residence times can be found in Table 3. In addition, tree ages of individual species were compared and are shown in Table 4. On average, *P. abies* logs were older ($p < 0.001$) with 56 years than logs of *F. sylvatica* (43.9 years). *F. sylvatica* logs with the largest number of tree rings were in fact dated in Mazák 1 (48.2 tree rings), whereas the oldest *P. abies* logs were encountered in Mazák 2 (64.6 tree rings).

Negative exponential relationships in depletion rates were obtained for cross-dated *F. sylvatica* and *P. abies* as functions of the cumulative relative abundance of cross-dated wood pieces, total and in-channel wood volumes, and instream wood residence times. The resulting depletion coefficient *k* notably differs for individual species (Fig. 4). Lower values of depletion coefficients and, thus, potentially slower decay rates were obtained for *P. abies* ($k = 0.028$ for the number of dated pieces and $k = 0.034$ and $k = 0.035$ for the total and in-channel wood volumes, respectively) when compared to *F. sylvatica* logs ($k = 0.066$ for the number of dated pieces and $k = 0.069$ and $k = 0.075$ for total and in-channel wood volumes respectively).

The residence time was then compared with the following log parameters so as to reveal possible influencing factors: (i) log diameter, (ii) mean annual radial increment rate, (iii) number of tree rings per log (or log age), and (iv) the proportion of log length located in the active

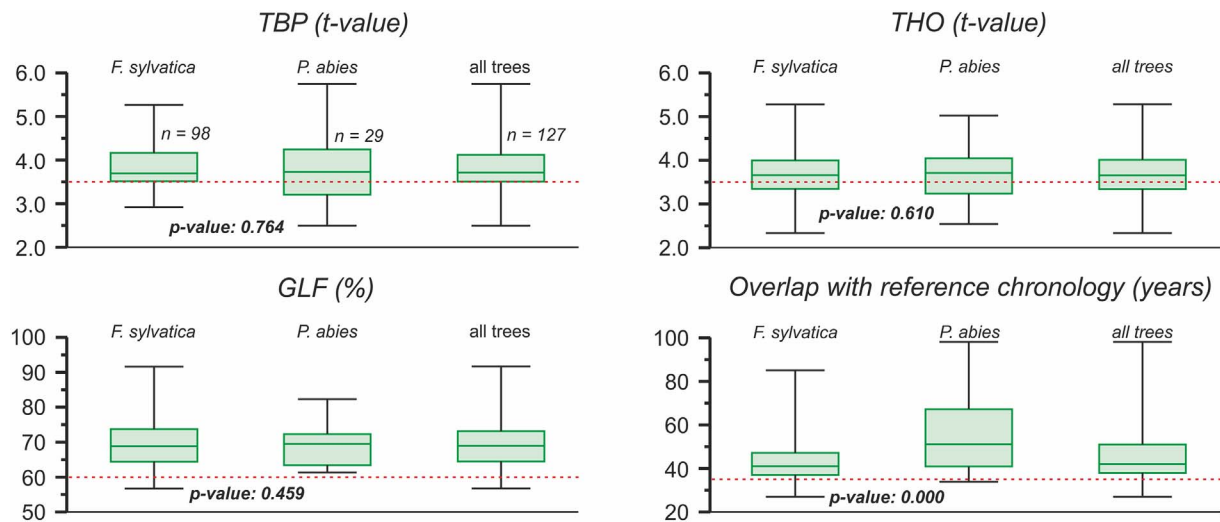


Fig. 2. Overview of cross-dating statistics for the samples of two analysed tree species and the sample of all logs (p values show differences as tested by the Mann-Whitney test). TBP stands for the t-test following Baillie and Pilcher (1973), THO was assessed with the t-test following Hollstein (1980), and GLF (%) indicates the coefficient of agreement (or Gleichläufigkeit). Horizontal dashed lines show the minimal thresholds used for cross-dating to be considered successful.

channel (as an indicator of log proportion influenced by flowing water and/or wetting/drying cycles). Fig. 5 and Table 5 provide details on this analysis. A significant positive correlation with log age was found at all individual streams as well as for the entire study (and for both tree species). In addition, significant correlations with log diameter were also found in the case of *F. sylvatica*. A negative, yet not significant, correlation was detected between residence time and increment growth rate in all streams. By contrast, no significant correlations were detected for the proportion of logs located within the active channel.

No statistically significant relationships were observed between expected wood piece shortening and instream wood residence times, neither for the entire dataset nor for individual tree species (Fig. 6). Not significant power relationship can be expressed only for *F. sylvatica* with $R^2 = 0.07$, pointing to a shortening of instream wood pieces with increasing residence time.

The *P. abies* logs were generally longer and thicker than the *F. sylvatica* logs ($p = 0.035$ and $p < 0.001$ respectively). At the same time, however, we also observe that instream wood orientation is practically independent of wood length or mean diameter and that apparent differences thus existed between the orientations of wood pieces between the investigated species (Fig. 7). Instream wood of *F. sylvatica* was often orientated perpendicularly to flow direction reflecting its frequent hillslope stabilisation (stability class B), whereas *P. abies* logs showed a higher proportion of wood orientated parallel to the flow direction. This was also reflected in the comparison of wood orientation and dated tree deaths. The logs with longer residence time were frequently orientated parallel to the main flow direction, primarily as a result of the longer observed residence times of *P. abies* logs. In addition, wood orientation of *P. abies* logs showed a relationship with wood residence time ($R^2 = 0.12$ for the second degree of polynomial fit) with a peak close to 90° (see Fig. 7). This implies that *P. abies*

instream wood pieces with longer residence times were prone to flow-parallel orientations. We did not observe any similar tendencies for *F. sylvatica*.

4.3. Relationship between the wood residence time and visually determined wood parameters

We then compared decay classes with wood residence times for the entire sample and then again separately for the two species (Fig. 8). Significant differences exist between decay classes 1–3 for the entire sample and each of the two species. In the case of *P. abies*, we were able to compare only classes 2 and 3, as only one *P. abies* log falling into class 1 could be dated successfully. We observe significant differences between the tested classes for *P. abies* but have to underline the extremely low number (4) of observed *P. abies* logs in decay class 2.

Instream wood assigned to particular stability classes differed significantly in residence time. Instream wood included in class B (i.e., hillslope-stabilised pieces) was significantly younger than the pieces belonging to class A (i.e., unattached wood) or to class C (i.e., wood pieces stabilised by bed sediments or other wood) (Fig. 9). Consequently, we tested significance of differences in residence time between stability classes of wood pieces from individual tree species. The *F. sylvatica* instream wood belonging to class B was younger when compared to instream wood of class C. However, we did not observe any significant differences in residence time between *P. abies* wood pieces assigned to particular stabilisation classes.

The residence time of functional and nonfunctional wood did not differ in the studied streams. Five dated *F. sylvatica* logs and two *P. abies* logs acted as steps and 24 instream wood pieces (17 *F. sylvatica*, 7 *P. abies*) were incorporated into jams (Table 6). The mean residence time of log steps created by *F. sylvatica* did not differ from the mean of all

Table 2
Overview of dating successfulness and cross-dating statistics of successfully cross-dated logs.

	Maz1			Maz2			Maz3	All streams		All trees
	<i>F. sylvatica</i>	<i>P. abies</i>	Total	<i>F. sylvatica</i>	<i>P. abies</i>	Total	<i>F. sylvatica</i>	<i>F. sylvatica</i>	<i>P. abies</i>	
Samples	51	30	81	35	6	41	67	153	36	189
Successfully dated (%)	35 (68.6)	24 (80.0)	59 (72.8)	22 (62.8)	5 (83.3)	27 (65.9)	41 (61.2)	98 (64.1)	29 (80.6)	127 (67.2)
Mean TBP	3.98	3.81	3.91	3.77	3.70	3.76	3.74	3.83	3.79	3.82
Mean THO	3.55	3.65	3.59	3.71	3.62	3.69	3.85	3.70	3.64	3.69
Mean GLF	68.99	69.08	69.02	71.39	70.04	71.13	69.45	69.73	69.25	69.62
Mean overlap with reference chronology (years)	48.2	54.1	50.6	42.9	64.6	46.9	40.4	43.9	56.0	46.6

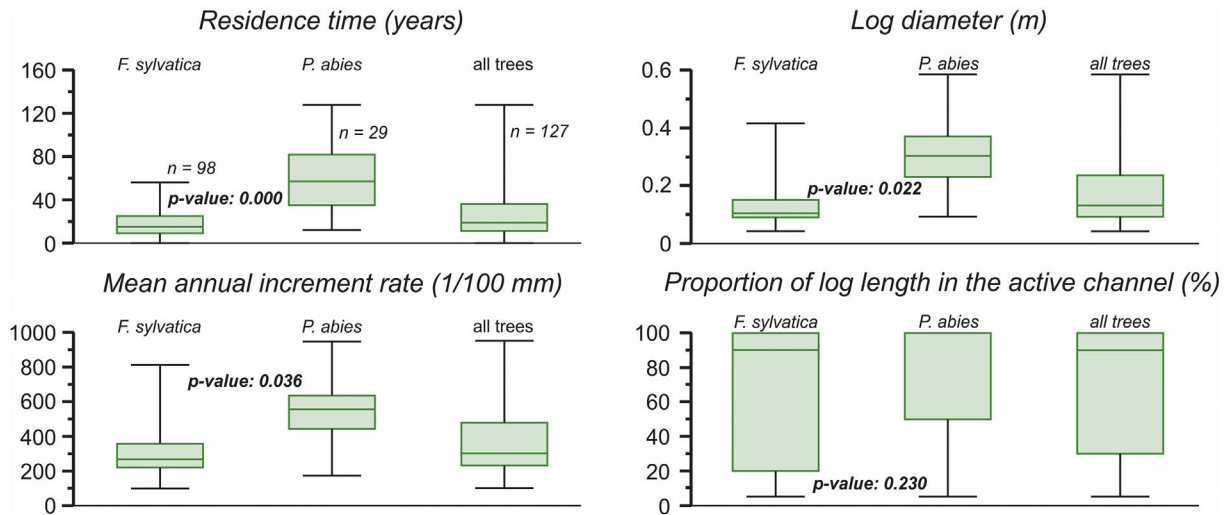


Fig. 3. Residence time of logs and overview of log parameters that are thought to influence instream wood residence (p value shows the differences tested with the Mann-Whitney test).

Table 3
Overview of residence time of all successfully dated logs.

Stream	<i>F. sylvatica</i>			<i>P. abies</i>		
	Mean (stdev)	Maximal	Minimal	Mean (stdev)	Maximal	Minimal
Mazák 1	21.0 (14.9)	56	0	59.9 (30.0)	128	12
Mazák 2	10.3 (6.6)	24	1	48.2 (12.3)	61	30
Mazák 3	20.9 (12.4)	56	5	–	–	–
Total	18.4 (12.5)	56	0	57.9 (27.9)	128	12

Table 4
Overview of tree ages of all successfully dated logs at the time of death.

Stream	<i>F. sylvatica</i>			<i>P. abies</i>		
	Mean (stdev)	Maximal	Minimal	Mean (stdev)	Maximal	Minimal
Mazák 1	48.2 (13.9)	85	35	54.1 (15.6)	98	37
Mazák 2	42.9 (10.5)	65	28	64.6 (24.4)	97	34
Mazák 3	40.3 (8.2)	61	27	–	–	–
Total	43.9 (11.5)	85	27	56.0 (17.4)	98	34

dated *F. sylvatica* instream wood pieces (also compare data with Table 4). In addition, the residence time of *F. sylvatica* and *P. abies* incorporated into jams did not significantly differ from that of instream wood outside these jams ($p = 0.70$ and $p = 0.95$ respectively). However, these results may be affected by the relatively low number of dated wood pieces with geomorphic function, especially in the case of *P. abies*.

5. Discussion

In this study, we successfully dated the year of death of 127 out of 189 initially selected logs in steep headwater channels in the flysch Carpathians. We observed that the *P. abies* logs could be easier cross-dated (80.6%) than *F. sylvatica* logs (67.2%), a fact that could be related to difficulties in a proper identification of tree-ring boundaries in *F. sylvatica* (even if wood quality was sufficient for a sampling based on increment cores). In addition, *F. sylvatica* is also known to be a strongly competitive species (Janík et al., 2016) and that individuals can react with growth releases after the elimination of neighbouring trees (for details see Stoffel et al., 2005; Stoffel and Bollschweiler, 2008). These irregularities (or growth disturbances) can significantly hamper cross-dating or even render it impossible. The cross-dating results also

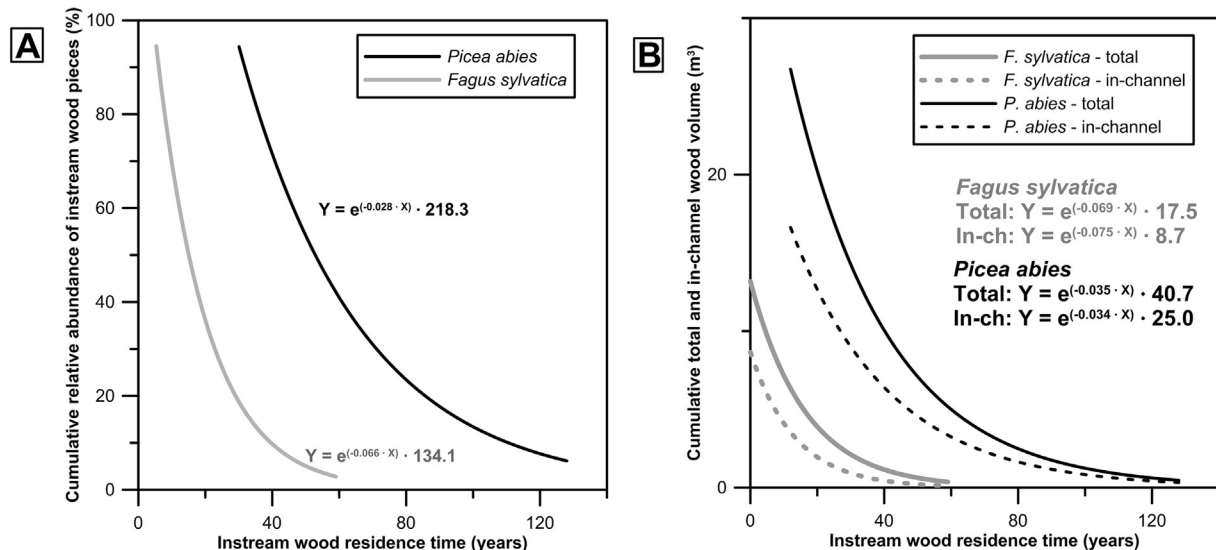


Fig. 4. Comparison of exponential depletion curves for *P. abies* and *F. sylvatica* in the studied streams. (A) Assessment by cumulative relative abundance of instream wood pieces, (B) assessment by total and in-channel (In-ch) volume.

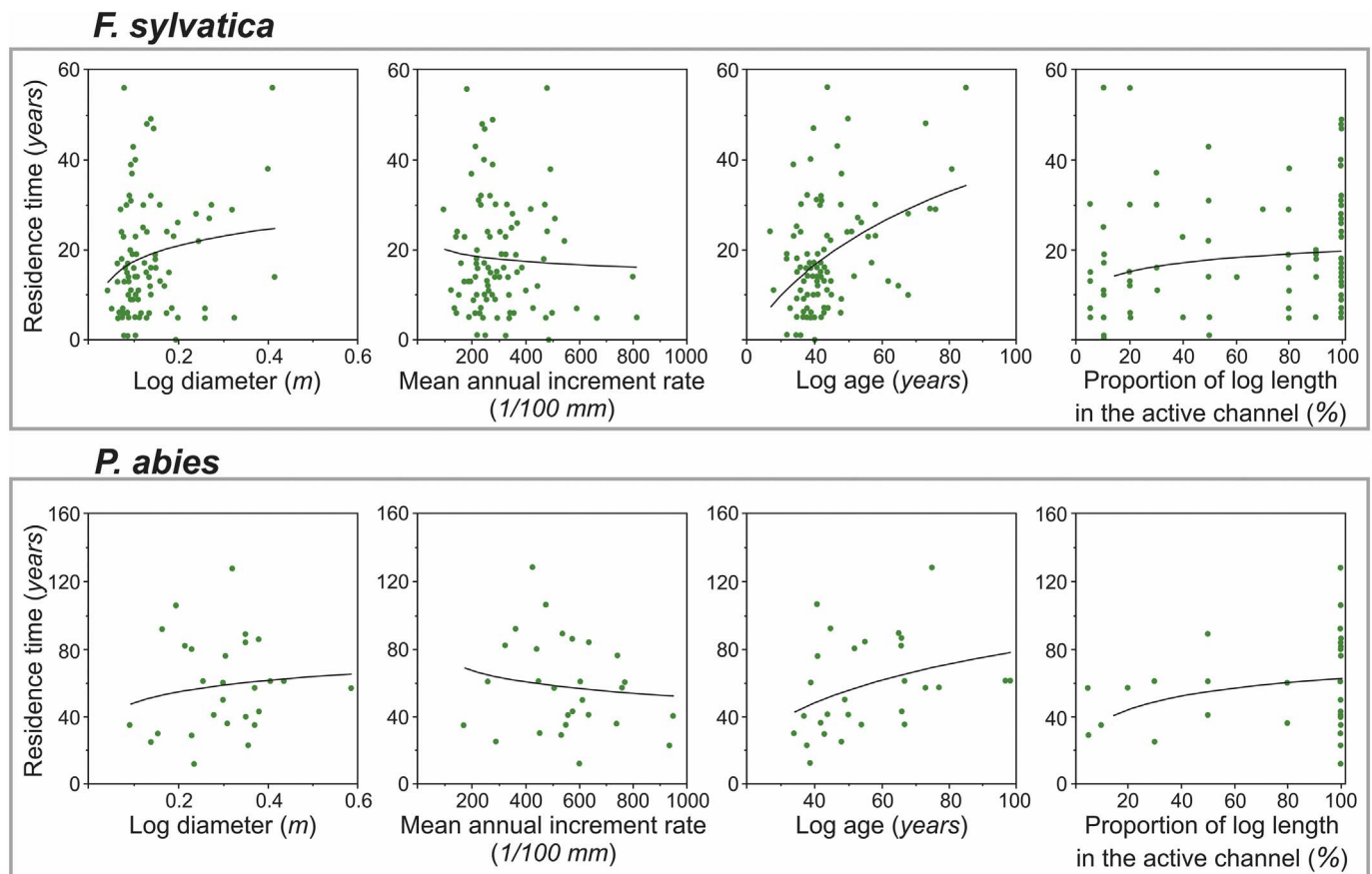


Fig. 5. Relationships between log residence time and selected log parameters.

Table 5
Correlation coefficients between the residence time and selected wood parameters.^a

Wood parameter	Maz1		Maz2		Maz3	All streams	
	<i>F. sylvatica</i>	<i>P. abies</i>	<i>F. sylvatica</i>	<i>P. abies</i>		<i>F. sylvatica</i>	<i>F. sylvatica</i>
Log diameter	0.194	0.098	0.074	Too low N for calculation of significance level	0.142	0.204	0.097
Mean annual increment rate	-0.179	-0.241	-0.280		-0.124	-0.082	-0.217
Log age	0.559	0.355	0.669		0.386	0.434	0.320
Proportion of log length in the channel	0.058	0.329	0.276		-0.073	0.133	0.247

^a Statistically significant correlations at $p = 0.05$ are bolded.

depend on the length of the overlap of a specific sample with the reference chronology. As *P. abies* trees were significantly older than *F. sylvatica* trees, the overlap with the reference chronology was typically longer too, such that statistical thresholds were passed more easily in terms of cross-dating and with greater success in the case of *P. abies*.

5.1. Residence time of instream wood

Previous works documented that conifers are usually preserved over longer periods in stream channels as compared to deciduous species (Hyatt and Naiman, 2001; Díez et al., 2002; Dahlström et al., 2005). This finding was confirmed in our case as longer residence time was observed for *P. abies* instream wood (mean of 57.9 years) as compared to *F. sylvatica* logs (mean of 18.8 years). Our findings thus also correspond well with the results of cross-dating studies based on large wood lying on the floor of Carpathian forests; these studies also documented that *F. sylvatica* would disintegrate within a period of max. 50–60 years (Šamonil et al., 2009) and that the decomposition time of *P. abies* would be reported in the range of 100–150 years (Holeksa, 2001). The maximal residence time of *P. abies* instream wood

in Mazák was in fact, comparable to the values presented above and similar to that of cross-dated *P. abies* in Swedish boreal streams (ca. 100 years), but significantly shorter as compared to Scots pine (*Pinus sylvestris*) trees from the same region (up to 300 years; Dahlström et al., 2005). Markedly shorter maximal residence times were obtained for *P. abies* (ca. 60 years) in a headwater channel in the Gorce Mts. (Poland); this difference can most likely be explained by the fact that instream wood was removed by local people until the 1980s (Kaczka, 2009). In addition, the mean residence time of instream *P. abies* stored in log jams in an Alpine headwater stream of Switzerland reached only 1.5–11.5 years (Jochner et al., 2015). By way of example, 20% of all dated instream conifer pieces were older than 50 years in mountain streams of the Pacific Northwest, and two pieces were even extraordinarily old with > 1300 years based on a combination of tree-ring and ¹⁴C dating (Hyatt and Naiman, 2001).

The decay or depletion coefficient of instream wood, k , points to an exponential loss of mass, density, volume or number of wood pieces per year. In the literature, a wide range of values between 0.01 and 3.10/y is usually reported, which depends on the approach used, tree species, wood size, water chemistry, and climate (Bilby et al., 1999; Díez et al.,

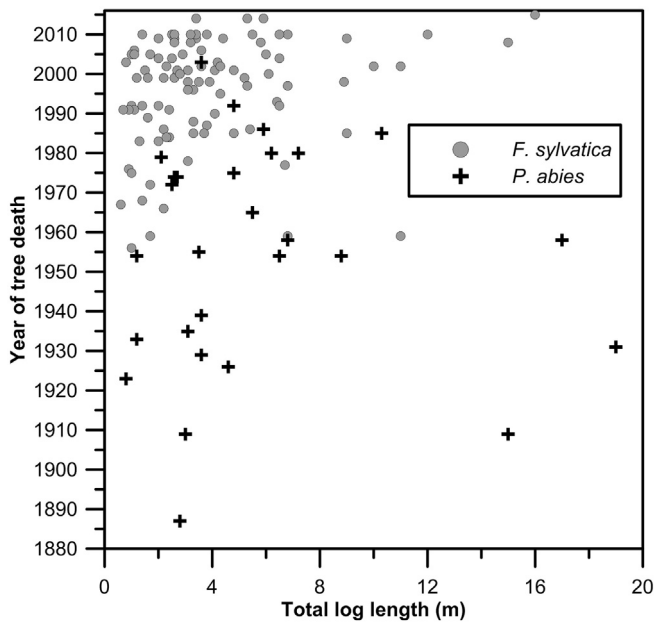


Fig. 6. Relationship between total log length and instream wood residence time for *F. sylvatica* and *P. abies*.

2002; Scherer, 2004; Ruiz-Villanueva et al., 2016; Wohl, 2017). In our case, the values ranged from 0.028 to 0.035 for *P. abies*, which corresponds well with the k value of 0.030 as reported for a decreasing number of large conifer pieces in a stream of the Pacific Northwest (Hyatt and Naiman, 2001). The *F. sylvatica* samples indicated a ca. 2.5-fold higher intensity of depletion rates at the Mazák streams ($k = 0.066–0.075$). Díez et al. (2002) investigated the breakdown of small wood pieces (1 m in length, 0.03 m in diameter) in a stream of the Iberian Peninsula. They reported generally higher k values for the loss of mass of pine pieces (0.016–0.067) as compared to those of Mediterranean deciduous species (0.058–0.271); the conclusion of that study, however, was that small wood breakdown appeared to be most sensitive to stream water chemistry. Thus, the presence of conifers in our case may have increased the volume of instream wood in these mixed forests as a result of longer residence times. At the Mazák streams, *F. sylvatica* trees frequently supply wood pieces of relatively

small dimensions (more frequently in the form of individual branches with diameters < 0.1 m than individual trees) (Galia et al., submitted), but their faster depletion (mean observed residence time of *F. sylvatica* was 18.4 years against 57.9 years for *P. abies*) typically prevents overloading these channels with relatively small wood of local deciduous species.

The assessment of tree mortality and the dating of death years do not necessarily provide details on the year of tree delivery to the channels. Therefore, it is possible that some of the dead trees may have remained outside the stream for some time before they actually entered the active channel. Our assumption is that the steep gradient of the adjacent hillslopes ($0.8 < S < 1.2$ m/m), together with their frequent waterlogging related to high amounts of precipitation (mean of 1390 mm/y in the study area), notably decreases stability of wood pieces (i.e., their residence time on the adjacent hillslopes), so that their delivery to the channel should be rather quick. Therefore, we assume rather short lapse time periods between dated tree deaths and their entrance into the fluvial systems. This statement corresponds with our observation that logs stabilised by hillslopes (class B) are younger than pieces that are entirely located in the active channels (classes A and C). In fact, the only exceptions to this could in fact be two pairs of dated logs of class B that initially acted as ‘bridges’ anchored on either side of the hillslopes and above the bankfull depth (sensu Wohl et al., 2010). These two logs were later broken in situ into pairs of shorter ‘ramps’ as a result of their advanced decay but still interact directly with the active channel. The conceptual model of instream wood dynamics assumes this type of potential wood supply into narrower headwater streams and confirms the frequent occurrence of ‘bridges’ (Jones et al., 2011).

5.2. Local flood events and potential instream wood recruitment

The supply of wood into the studied channels is controlled by individual tree mortality, snowloading, windstorms, or shallow hillslope mass movements. Especially the last agent can be related strictly to the occurrence of high precipitation amounts and thus also trigger floods. Floods in the area are connected to long-term, intensive cyclonic precipitation or to flash floods produced by convectional storms in the area of Lysá hora Mt. By contrast, snowmelt floods are quite rare (Šilhán, 2015). Based on this background, we plotted annual tree mortality over the period 1957–2010 against a dendrogeomorphic reconstruction of hydrogeomorphic events available for 10 streams

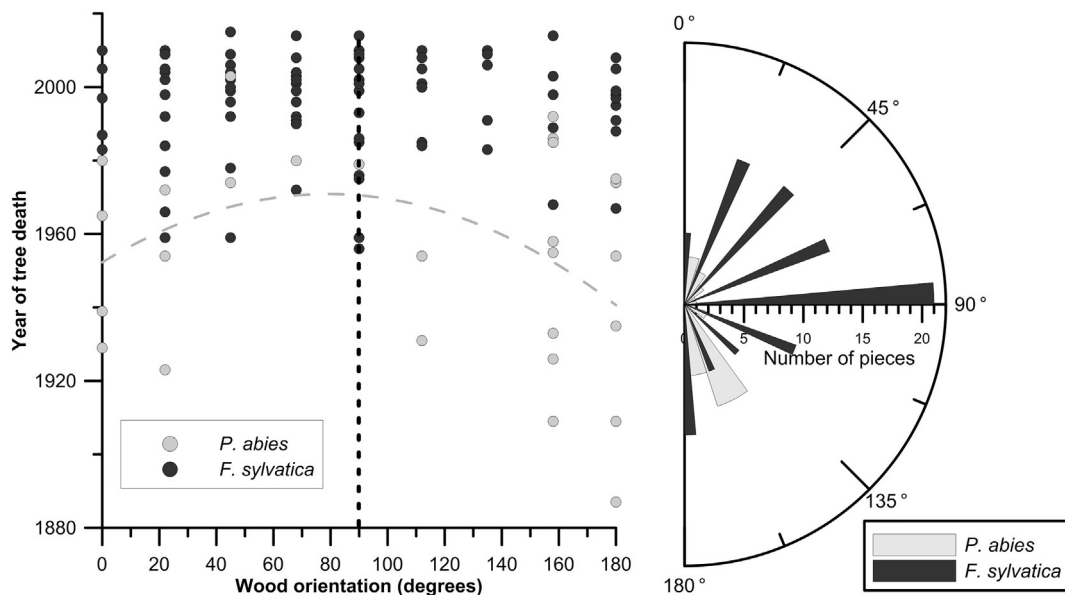


Fig. 7. Orientation of wood – comparison of individual tree species (right) including the year of tree death (left). The grey dashed line indicates the second degree of polynomial fit between wood orientation and the year of tree death for *P. abies* logs.

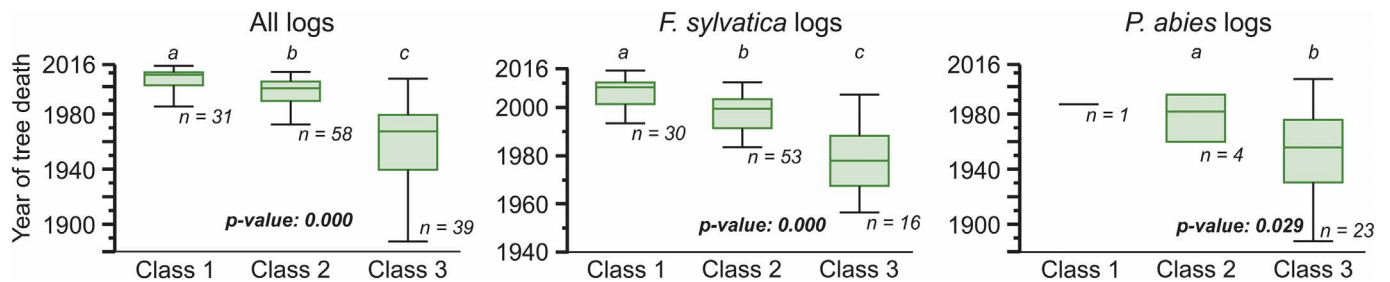


Fig. 8. Boxplots of decay classes related to years of tree death for the entire data set (left), for *F. sylvatica* (middle) and for *P. abies* (right). Letters indicate significant differences between the groups indicate by the Mann-Whitney *U* test (*P. abies* data set) and Fischer's LSD post-hoc test (other data sets).

draining the Lysá hora Mt. (for details see Šilhán, 2015) as well as against maximal annual discharge from the nearby Satina basin, which drains the western slopes of the Lysá hora Mt. ($A = 7.7 \text{ km}^2$, discharge data available since 1957, for geographical position see Fig. 1).

Interestingly, some of the years with recorded and reconstructed floods (e.g., 1958, 1972, 1985, 2010) coincide with the years of increased tree mortality in the Mazák streams, and therefore provide evidence for the existence of causal links between rainfall-triggered mass movements and the supply of instream wood for several cases (Fig. 10). At the same time, however, several other years with increased tree mortality (e.g., 1975, 1998) are not apparently related with flood events, even if high precipitation amounts in the years preceding mortality could have acted as triggers of slope instabilities, a process that occurs quite often in the flysch-based lithological structures of the Moravskoslezské Beskydy Mts. (Pánek et al., 2011a). In a similar way, not all observed floods caused notable increases in tree mortality. By way of example, the floods of 1996 and 1997, which had recurrence intervals of 20 years, did not result in increased tree mortality and large wood input at our study sites. It is, therefore, likely that windstorms and snowload may have contributed to tree death, but no data were available to test this hypothesis. Evidence of fire is, by contrast, lacking in the field; and thus, fire should not be considered as a potential trigger in our case.

5.3. Residence time vs. selected wood parameters

Typical wood decomposition rates of individual tree species depend on internal as well as on external variables, such as wood submergence, water chemistry, or climatic conditions. Above all, however, they also depend on log size (which is often seen as a function of log age), whereby smaller pieces have a higher surface area to volume ratio than larger pieces. As a result, microbiological decomposition of smaller logs will be faster (Spänhoff and Meyer, 2004). Holeksa et al. (2008), for instance, documented the dependence of the residence time of *P. abies* on log diameter on forest floors in Carpathian catchments. The authors observed a mean residence time of 71 years for log diameters < 23 cm, 90 years for diameters in the range of 23–35 cm, and 113 years for the largest logs exceeding diameters of 35 cm. At our study site, a diameter-dependence of decomposition rates (and thus residence time) can be found for the entire data set of *F. sylvatica* logs. However, we

Table 6

Overview of residence time of wood based on its geomorphic function.

Function	<i>F. sylvatica</i>			<i>P. abies</i>		
	Mean (stdev)	Maximal	Minimal	Mean (stdev)	Maximal	Minimal
Step	18.4 (11.9)	41	6	26 (19.8)	41	13
Jam	19.9 (11.8)	50	7	63.4 (29.8)	107	20

cannot confirm such relationships either at the level of individual streams (most likely as a result of limited sample size) or for the full data set of *P. abies* instream wood. In fact, even rather thin conifer logs frequently had well-preserved wood structures and could thus be used for cross-dating over multiple decades after tree death and transport into the channels.

At our sites, the negative (yet nonsignificant) correlation between mean annual increment rate and residence time may also suggest the next possible effect of wood property on decay rates. Tree-ring width (a parameter reflecting annual increment rate) is well known to tend to correlate strongly with wood density, particularly so in the case of *Picea* (Bergqvist, 1998; Pape, 1999). As a consequence, high wood density tends to decrease decay rates directly as a result of (i) its high ability to retain water that in turn limits gas exchange, thus leading to oxygen depletion and a subsequent decrease in decay activity of most fungi (Boddy, 2001), or as a result of (ii) low wood porosity that inhibits the spread of hyphae (Edman et al., 2006). As such, low mean annual rates can indeed increase log residence time, and this may be the case at our study sites.

No significant relationship was observed when total log lengths and instream wood residence times were compared for the entire data set or for individual tree species. Instead, we only observed poor, insignificant relationships between residence time and log length for *F. sylvatica* (Fig. 6). In our case, a clear relation between the assumed shortening of wood pieces (owing to the occurrence of decomposition processes and/or abrasion/breakage during potential wood transport) and increasing residence time apparently does not exist. A positive, yet insignificant relationship between log residence time and the proportion of a log within the active channel most likely resulted from the more frequent parallel orientation of *P. abies* logs to flow direction, together with their

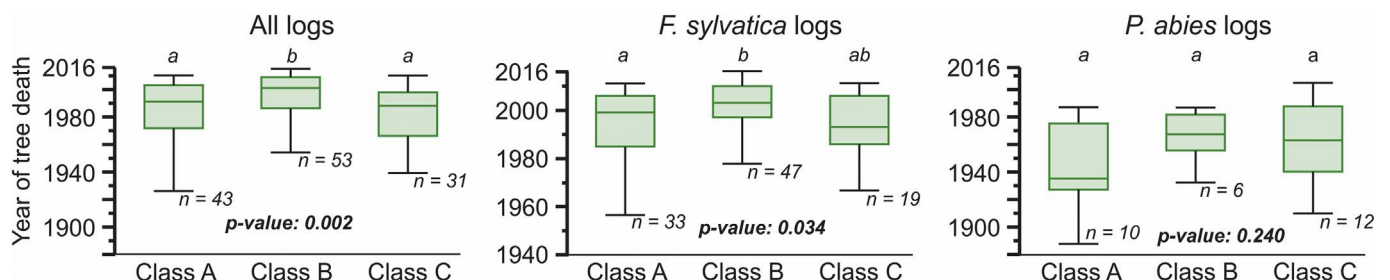


Fig. 9. Boxplots of stabilisation classes related to years of tree death for the entire data set (left), for *F. sylvatica* (middle) and for *P. abies* (right). Class A – unattached wood, class B – hillslope-stabilised wood, class C – wood stabilised by bed sediments or other wood. Letters indicate significant differences between the groups obtained by Fischer's LSD post-hoc test.

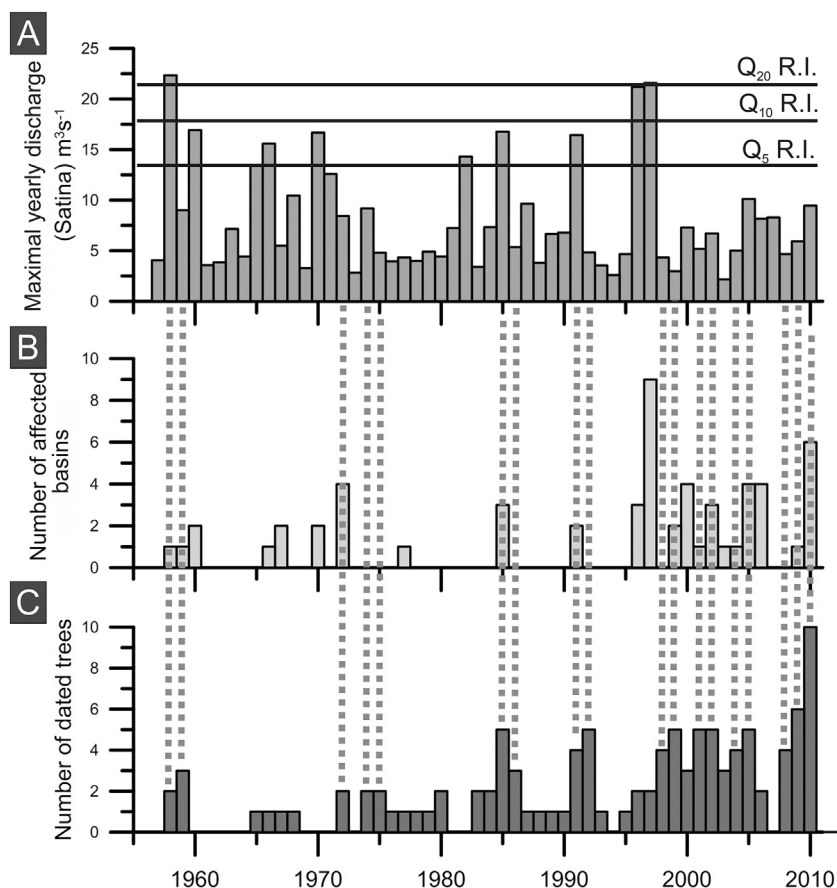


Fig. 10. Comparison between gauge records from the Satina Stream with discharge recurrence intervals (A), hydrogeomorphic process activity in 10 basins draining the Lysá hora Mt. (derived from Šilhán, 2015) (B), and the number of cross-dated instream wood pieces in the Mazák streams originating from trees that died in particular years (C). Dashed lines indicate the flexible threshold used for different periods of the past, i.e., two dated pieces per year for the 1950s–1970s, three dated pieces per year for the 1980s and 1990s, and four dated pieces per year for the twenty-first century.

longer residence times (see Fig. 7).

Narrow headwater channels usually have limited capacity to transport large wood (Hassan et al., 2005; Jones et al., 2011). As a consequence, instream wood is usually reported to be randomly oriented in these narrow channels (Comiti et al., 2006; Jones et al., 2011). In the case of the Mazák streams, however, the generally longer residence times of *P. abies* instream wood apparently resulted in more specific patterns of log orientation as compared to those observed in the considerably younger *F. sylvatica* logs. In fact, we found more frequent orientations of *P. abies* parallel to the flow direction, which suggests log movement and/or changes in orientation with respect to the flow direction would have been affected by a larger number of flood events during the time of their residence in the fluvial system. This observation could also be related to the relatively high intensity of bedload transport and the occurrence of small debris flows (Šilhán, 2012; Tichavský et al., 2014; Galia et al., 2015; Šilhán et al., in review). On the other hand, we did not find any differences in residence times between wood pieces incorporated into log jams and individual pieces outside these jams. As active transport of individual logs before their incorporation into log jams is usually assumed (Montgomery et al., 2003; Wohl and Cadol, 2011), we thus think that fairly small changes in wood orientation or relatively short transport distances may prevent the formation of large log jams and therefore also control spatial dynamics of instream wood in the headwaters analysed in this study. The only exception to this observation is one large log jam found in Mazák 1, which consisted of > 60 LW and SW pieces. The present position of the jam was predisposed by the occurrence of debris flow accumulation changing the valley morphology, and many logs were deposited in the narrower channel. An additional hillslope wood supply

contributed to the stabilisation of the jam (Šilhán et al., in review).

An additional explanation for the frequent wood orientation (parallel to the flow) of the longer residence time logs could be related to hillslope processes. Relatively recently fallen trees could be stabilised on hillslopes by large soil or regolith masses attached to their rootwads, by the rootwads themselves, or by remaining branches. With time, soil would be washed out by rainfall and rootwads together with branches would be subjected to decay as they are thinner than logs and as they would permanently remain at subaerial conditions. As this happens, the ends of logs resting on valley slopes can be reoriented by creeping or sliding snowpack, and this could indeed change the previously oblique or near-perpendicular orientation of the logs to parallel positions. However, we did not observe any change in the orientation of *F. sylvatica* logs, even after increased residence time, despite the fact that a majority of the cross-dated pieces lacked rootwads or branches. In addition, we documented only 8 of 53 pieces (both *P. abies* and *F. sylvatica*) with residence time equal to or larger than 30 years and which were still hillslope-attached. It implies that changes in wood orientation with respect to decreasing stabilisation effects of rootwads or branches would take place only during the early decades after tree death. One should also note that hillslopes adjacent to the studied streams are very steep, which considerably decrease stability of hillslope-attached wood.

Observed decay classes (classes 1, 2, and 3) at the study sites correlated well with cross-dated ages of logs in case that individual decay classes were compared with each other. At the same time, however, visually-based decay classes were not a particularly good indicator of log residence time in the case of *P. abies* or *F. sylvatica* (Fig. 8). Such limitations have previously been described by Hyatt and

Naiman (2001) and could be related to the fact that wood decomposition rates depend on many other factors than time (Díez et al., 2002; Scherer, 2004; Ruiz-Villanueva et al., 2016; Wohl, 2017).

6. Conclusions

At the steep headwater catchments of the Carpathian mountains, mean and maximum residence times of instream wood differed by a factor of two between *Picea abies* and *Fagus sylvatica*, with the first reaching much larger values. In addition, log age and log diameter seem to play an important role in the preservation of wood pieces in the fluvial system, whereby generally older and thicker pieces indicate longer instream wood residence times, especially in the case of *F. sylvatica*. Obtained results indicate that potential changes in tree riparian compositions (e.g., tree species and age) of mixed temperate forests will also directly lead to changes in instream wood abundance, not only via quantitative changes in wood recruitment, but also in depletion rates of individual wood pieces. Noteworthy, we were also able to determine residence times of logs using tree rings and the application of additional methods (e.g., ^{14}C dating) might, in fact, provide information on much longer residence times in the case of more decayed wood before its total depletion from the channel.

Observed residence times of instream wood with specific geomorphic functions (such as steps and jams) did not differ from nonfunctional wood. We also did not obtain any significant correlation between wood residence time and total wood length. Nevertheless, we observed changes of instream wood orientation with respect to wood residence time. This finding points to at least some partial mobility (e.g., changes in log orientation or short-distance fluvial transport) of instream wood, which also included pieces longer than the channel width ($1.5 \leq W \leq 3.5$ m). Based on the above findings and the remaining challenges, we call for additional research dealing with the monitoring of instream wood transport, not only in larger-scale gravel-bed or lowland meandering rivers, but also in mountain headwaters, where the frequent mobility of instream wood by fluvial transport is not generally considered.

Acknowledgements

The authors sincerely appreciate the comments and suggestions of anonymous reviewers and Editor-in-Chief Richard A. Marston. This study was funded by a project of the University of Ostrava Foundation: SGS05/PřF/2017–2018.

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